ASSESSING THE TREATMENT OF

AIRBORNE TACTICAL HIGH ENERGY

LASERS IN COMBAT SIMULATIONS

THESIS

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Maurice C. Azar

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Abstract

In March 2000, the High Energy Laser Executive Review Panel presented the Department of Defense Laser Master Plan, which reported that HEL weapons are ready for offensive and defensive applications. One candidate platform capable of performing some of the reported applications is the Advanced Tactical Laser (ATL), an Advanced Concept Technology Demonstration program which places a high energy laser weapon on a tactical aircraft, such as the V-22, C-130, or H-47. A way of assessing the utility of a new weapon system and the benefits of its inclusion in the force structure is the use of combat models. This research examines, by example, issues involved with modeling an airborne tactical high energy laser weapon in a mission level combat simulation, and evaluates possibilities to aggregate simulation results into higher level, campaign models.

ASSESSING THE TREATMENT OF AIRBORNE TACTICAL HIGH ENERGY LASERS IN COMBAT SIMULATIONS

1. Introduction

Background

In March 2000, the High Energy Laser Executive Review Panel, a group comprised of representatives of organizations with potential interest in High Energy Laser (HEL) technology convened by the Deputy Under Secretary of Defense (Science and Technology), presented a report titled the Department of Defense Laser Master Plan. Within the document, the panel reported that HEL weapons are ready for offensive as well as defensive applications. The report mentions some unique possibilities for employment of laser weapons, such as engaging high speed and highly maneuverable targets, deliver lethality at light speed, and apply graduated power for non-lethal applications.

In 1994, the Department of Defense began a series of programs designed to decrease the amount of time between the formulation of an operational user's idea for a new warfighting capability and the assessment of that capability. Dubbed Advanced Concept Technology Demonstrations (ACTD), the programs are designed to help users better understand proposed warfighting capabilities, refine the concept of operations of those capabilities, evolve operational requirements, and evaluate a prototype of the

capability in a military demonstration (Intro., 2002). In fiscal year 2001, an ACTD named the Advanced Tactical Laser (ATL) was created (Descriptions, 2002).

The ATL ACTD, sponsored by United States Special Operations Command, proposes to place a HEL weapon on tactical aircraft, such as a V-22, H-53, C-130, or H-47. The focus of the ACTD is the precise placement of potentially lethal energy on a target in order to mitigate collateral damage. The proposed maximum effective range is 15 kilometers (Descriptions, 2002) with an expected power output of 70 kilowatts (Erwin, 2002).

A similar undertaking is underway at the Air Force Research Laboratory (AFRL). The AFRL variant of a proposed tactical HEL weapon, possibly to be mounted on aircraft such as the F-15, F-16, F/A-18, the F-35 Joint Strike Fighter, and unmanned combat air vehicles, is expected to be demonstrated by the end of 2004. Further development of the program is expected in later years to boost the weapon's power to 100 kilowatts (Sirak, 2002).

Both the ATL ACTD and the AFRL tactical HEL effort are developing technologies to provide new military capabilities. One of the ways to assess the performance of the new capability is simulation. According to Law and Kelton, simulation is a "useful and powerful tool" to aid in "evaluating military weapons systems." (Law, 2000:3)

Research Problem

The current state of High Energy Laser (HEL) modeling may be generally characterized by multiple independent engineering models, which address only a small

spectrum of a HEL engagement. Some models have been created for single purposes such as laser generation, atmospheric propagation, beam control, and laser-target interaction. Many of these models are proprietary and are not designed to interface with other applications which model different aspects of an engagement. The HEL Joint Technology Office (HEL JTO), formed in June 2000 to manage a DoD-wide program to revitalize high-energy-laser science and technology research, has identified a need for end-to-end modeling of HEL capabilities. These "photon birth to death" models are particularly useful in the case of future weapon systems such as the Advanced Tactical Laser (ATL).

The technical nature of the engineering models makes them relatively difficult for non-experts to run, and they sometimes require long processing times. Therefore, the greatest utility for an operator based user community will be to aggregate the engineering models to an engagement or mission level. Though some combat models presently address an engagement for the Airborne Laser (ABL), few models exist for other HEL utilizations, such as the notional air-based Advanced Tactical Laser (ATL). One such model is the Extended Air Defense Simulation (EADSIM).

The HEL JTO has communicated a desire to raise awareness of capabilities of HEL weapons, such as the ATL, to senior leaders and decision makers. One way to do this is to incorporate HEL capabilities into combat models with which the target audience is more likely to be familiar. EADSIM, classified as a mission level model, is very useful to a large number of DoD analysts, but it does not maintain the high-level perspective senior leaders require. Such models are identified as campaign level models, and the Air Force's choice to date is THUNDER. With the difficulty of creating end-to-end

engagement models for HEL weapons, the question remains about the usefulness and accuracy of introducing HEL capability into the uppermost level of combat model aggregation, the campaign models.

Research Objective

This research effort has two objectives. The first objective is to document the potential treatment of an ATL weapon in a widely used combat simulation, EADSIM version 9.00b. To accomplish this objective, a notional scenario is created to evaluate the capabilities of EADSIM to model a HEL weapon, identify important characteristics of HEL weapons included at the mission level, and recommend potential additions or deletions to that set. Most importantly, the information input requirements and potential outputs are outlined. Additionally, measures of effectiveness for the simulation are identified, as well as their contribution and conduciveness to aggregation into higher-level models. The identification of valuable output from EADSIM and recommendations for its inclusion in campaign models like THUNDER is the second objective.

Scope

One area of interest to the JTO subgroup on lethality is the effectiveness of the ATL against cruise missiles, an application of HEL weapons considered less difficult by the Department of Defense Laser Master Plan. This effort addresses a scenario of a single ATL platform engaging multiple cruise missile targets. The focus is on the sensitivity of simulation results to variations in model input parameters.

The notional ATL was selected for study because of the broad range of targets it may possibly attack. The ATL is expected to be a HEL weapon mounted to an airborne

platform, such as a derivative of the C-130 Hercules or F-15 Eagle. Neither the ATL's mission nor its concept of operations has yet been established, so the study may also serve as an exploration into potential ATL capabilities.

Overview

The next four chapters provide detailed information and descriptions of this effort. Chapter two summarizes the literature pertaining directly to this research. Chapter three outlines the methodology used to explore the problem discussed in section 1.2. Chapter four presents the results of the analysis. Chapter five provides the author's conclusions and recommendations for future research.

2. Literature Review

Introduction

The Department of Defense (DoD) applies modeling and simulation tools in a variety of applications. Modeling and simulation provides benefits in training and education, as well as engineering, testing, and analysis (CRS, 1995:1). A review of literature reveals the DoD uses a number of modeling and simulation tools which possess a broad spectrum of detail.

In September 2002, the Air Force Institute of Technology's Center for Directed Energy hosted a workshop on HEL modeling and simulation. Participants included representatives from the military service academies, the Air Force Institute of Technology, the Naval Postgraduate School, the Naval Surface Warfare Center, the Space and Missile Defense Center, and industry. The workshop reiterated the JTO modeling and simulation program's responsibility for end-to-end modeling across multiple levels of detail. One of the objectives discussed was improvement in the modeling and simulation of HEL system performance and technology utility (Perram, 2002).

According to Northrop Grumman's Dr. Lynn Ebbesen, a challenge before the HEL modeling and simulation community is to create a "bridge" between the scientists and technologists, who primarily use very detailed models, and the operational users, who traditionally work with models encompassing greater breadth and relatively large force structures. On the "user" side of the bridge described by Dr. Ebbessen are models of a specific level of detail called mission level models. Two separate studies conducted at the mission level by the Applied Physics Lab and Boeing provide a glimpse

of current work in the HEL arena. The results of such work may someday be useful for inclusion in larger models at what is known as the campaign level.

Department of Defense Modeling & Simulation

As the acquisition cost of new weapon systems continues to increase, decisions about the technologies in which the DoD should invest become even more important. The DoD recognizes this fact and continues to seek solutions to reduce cost while maintaining quality. One such solution is combat modeling and simulation (CRS, 1995:2).

Combat models and simulations have a wide range of uses. Two notable purposes for this research are hardware acquisition and tactical development. Acquisition decisions such as investment justification, system design, and contribution of a system to mission effectiveness are commonly supported by combat models. These models may also be used to help evaluate new and modified tactical ideas (Hartman, 1997:1-5). In fact, the DoD currently uses modeling and simulation of HEL weapons to support decisions about weapon system design and performance in addition to using tools to perform engineering trade studies and make determinations about military utility (Perram, 2002).

In 1995, the DoD issued a master plan for modeling and simulation within the department. Part of the vision for DoD M&S is "to provide readily available, operationally valid environments for use by the DoD Components…to support technology assessment, system upgrade, prototype and full-scale development, and force structuring." Additionally, the DoD plan applies to a broad range of the level of forces

represented from "high-fidelity engineering models to highly aggregated, campaign-level simulations involving joint forces" (DoD 5000.59-P, 1995:2-1).

Contemporary models may represent various levels of forces with potentially different emphasis at each level (Hartman, 1997:1-4). The dimensions of resolution and aggregation are commonly used to describe a hierarchy of combat models. Aggregation is defined by DoD 5000.59-M as "the ability to group entities while preserving the effects of entity behavior and interaction while grouped." The same source defines resolution as "the degree of detail and precision used in the representation of real world aspects in a model or simulation." Figure 2.1, based on Dr. Miller's unpublished OPER 671 class notes, shows the hierarchical grouping of combat models with their associated levels of resolution and aggregation.

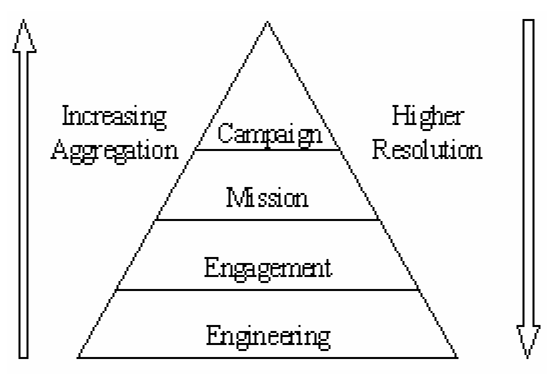

Figure 2. 1 Model Hierarchy

Mission Models.

In the middle tier of the model hierarchy are the mission models, which may permit modeling of larger combatant forces while retaining a high degree of resolution. Such resolution is obtained by maintaining the ability to model individual combatants as single entities (Caldwell, 2000:1-1). Mission models may use combinations of combatant

types to constitute a force in a mission or objective which may take hours of simulated time to accomplish (Mission, 2003). Currently, the Air Force Standard Analysis Toolkit utilizes the following models at the mission level:

- Extended Air Defense Simulation (EADSIM)
- Joint Integrated Mission Model (JIMM)
- System Effectiveness Analysis Simulation 2 (SEAS 2)
- Suppressor

Because EADSIM is currently one of the only models to incorporate HEL weapons at any level in the model hierarchy, it was selected for further study in this effort.

Extended Air Defense Simulation (EADSIM).

The Extended Air Defense Simulation (EADSIM), developed by Teledyne Brown Engineering, is a many-on-many simulation capable of modeling air, missile, and space warfare. It is managed by the Testbed Product Office of the U.S. Army Space and Missile Defense Command as the agent for the Ballistic Missile Defense Office (BMDO). Originally created to assist in the analysis of theater missile defense, EADSIM now models two-sided engagements of air, land, sea, and space assets with each side possessing attack and defense capabilities (Exec summary). Its scope and resolution allows modeling of, among other things, force movement, sensor activity and detection, combatant engagements, and endgame determination. Though EADSIM is sometimes identified as a theater level or campaign model, in practice, it is most often employed as a mission level model.

EADSIM version 9.00b supports the modeling of HEL weapons. Users may select from a number of laser weapons and behaviors, called rulesets, for air and ground

based scenarios. A notional ATL system is even included in the default database. The user is free to modify or create new entities and behaviors as required.

Over 390 users, including all U.S. military services, employ EADSIM. It has undergone numerous validation and verification efforts by U. S. Strategic Command, the Air Force Operational Testing and Evaluation Center, and many other user organizations. Accreditation has been performed by numerous joint and service organizations including BMDO. (Exec summary)

Campaign Models.

Campaign models represent the peak of the combat model hierarchy. They are characterized by the greatest levels of aggregation and lowest resolution. The large numbers of forces used in campaign models require more aggregation to remain within the operating limits of the computers used to run the simulations (Caldwell, 2000:1.1). Campaign models typically cover large geographical areas, have on the order of thousands of combatants, and may simulate scenarios spanning months (Hartman, 1997:1-5).

Most campaign level models are used to support senior decision makers. Topics of analysis may include the effectiveness of force structure, operational concepts, or the addition of new capabilities (Campaign, 2003). The Air Force Standard Analysis Toolkit utilizes the following models at the campaign level:

- THUNDER
- Combined Forces Assessment Model (CFAM)
- LCOM

The campaign level model most widely used for Air Force theater analysis is THUNDER. This research effort will focus on issues involved with the inclusion of a tactical HEL weapon in THUNDER.

THUNDER.

THUNDER is a stochastic, two-sided simulation of air, land, and naval warfare first introduced in 1986. Sponsored by the Air Force Studies and Analysis Agency (AFSAA) and developed and maintained by L-3 Communications Analytics Corporation (LAC), THUNDER may be run in one of two modes – analytical or wargame. The analytical mode supports typical simulation studies and analyses, while the wargame mode allows near real-time feedback and decision-making. Campaigns modeled in THUNDER may use varying levels of resolution based on user specifications.

The THUNDER Overview, Volume One of THUNDER documentation, only mentions the capability to model space-based lasers since version 6.7 released in March 2000 (Overview 15). However, the Methodology Manual, Volume Two, adds the possibility of using laser weapons in Theater Ballistic Missile Defense, as would be the case with the ABL (EADSIM Methodology, 2000:164). In Volume Three, Running THUNDER, an example of a report titled Daily Boost Phase Intercept Engagement Report identifies, and accumulates statistics for, a HEL Theater Ballistic Missile Defense weapon (Running 154). Clearly, THUNDER has the capacity to model HEL weapons to some degree.

Simulation Experiment

According to Law and Kelton, running a model is only a small part of a simulation study or experiment (Law and Kelton, 2000:83). Experimental design is necessary before simulation runs are completed. Once data from the runs is gathered, statistical analysis is usually required.

Design of Experiments.

Design of experiments refers to the method of planning an experiment so the results may be analyzed and valid conclusions may be drawn (Montgomery, 2001:11). Three principles governing experimental design are replication, randomization, and blocking. Replication refers to the repetition of an experiment and yields two benefits, possibility to estimate experimental error and obtain greater precision in the determination of the contribution of a factor to the experimental result (Montgomery, 2001:12). Randomization, accomplished by randomly allocating experimental material and experiment order, is used to ensure independence among trials and reduce or eliminate biases due to other factors which may be unwittingly introduced into the experiment (Montgomery, 2001:12). Blocking is the creation of a set of tests or trials with similar conditions to eliminate the variability due to factor which is known and controllable, but whose effect is not of interest (Montgomery, 2001:13, 126).

The method of experimental design begins with identification of a problem, selection the factors of interest and the values of those factors for which tests will be conducted, and determination of the response variable, or output of interest (Montgomery, 2001:14-15). Next, an experimenter must choose the experimental design which adheres to the principles of replication, randomization, and blocking

(Montgomery, 2001:16). After the experiment is conducted, analysis of results is performed and appropriate inferences are normally generated. One possible analysis technique is the Analysis of Variance.

Analysis of Variance (ANOVA).

Analysis of Variance (ANOVA) is a technique which determines the significance of a factor by comparing a test statistic generated from the mean square errors due to differences in the factor and errors in the model to an F distribution. The test statistic, F_0, for the single factor case is generated from the methods in the following table, based on Tables 3.3 from Montgomery. If the test statistic, F_0, is greater than the F statistic based on a-1 degrees of freedom in the numerator and N-a degrees of freedom in the denominator, then at least one of the treatments of the factor if interest has a statistically significant effect on the response.

Source of Variation	Sum of Squares	Degree of Freedom	Mean Square	F_0
Between treatments	$SS_{trtmnts} = n\sum_{i=1}^{a}\left(\bar{y}_{i\bullet} - \bar{y}_{\bullet\bullet}\right)^2$	a - 1	$MS_{trtmnts}$	$F_0 = MS_{trmnt}/MS_E$
Error (within treatments)	$SS_E = SS_T - SS_{trtmnts}$	N – a	MS_E	
Total	$SS_T = \sum_{i=1}^{a}\sum_{j=1}^{n}\left(y_{ij} - \bar{y}_{\bullet\bullet}\right)^2$	N – 1		

where N = total number of tests or runs

n = number of tests or runs at a given factor level

a = number of levels of factor

and the dot subscript notation $(\bullet)$ is used to represent summation over the subscript it replaces.

Previous EADSIM Missile Defense Studies

The simulations that later evolved into EADSIM were used primarily for analysis of missile defense. Simulation experiments in missile defense are still conducted using EADSIM. Johns Hopkins University and Boeing conducted two such experiments, selected for summary due to similarities with the scenario used in this research.

Applied Physics Lab.

The Applied Physics Lab (APL) at Johns Hopkins University used EADSIM for a number of studies in theater ballistic missile defense. In one study, APL randomized the placement of mobile TBM launchers and targets being protected by a ballistic missile defense ship within two respective circular regions in an attempt to account for uncertainty of launch and impact points. To accomplish the randomization, a pre-processing "script" was used. The measures of merit in the final analysis included the minimum, maximum, and average number of kills. (Monius and Pavalko, 2000)

Boeing.

Boeing's study supported the Airborne Laser (ABL) program using a simulation called the Layered Anti-Missile Defense Analysis (LAMDA) in an effort to evaluate the effectiveness of ABL platforms versus TBMs. LAMDA is an event driven simulation using the Airborne Laser (ABL) to engage multiple ballistic missile targets. Embedded in LAMDA is ABLPROP, a detailed laser propagation code. LAMDA is an analogous simulation to Integrated Strategic Architecture Analysis Code (ISAAC), the Schafer Corporation product chosen by the ABL System Program Office's to resolve ABL vs. ballistic missile engagements. The LAMDA model begins after target acquisition and uses a shortest time to kill selection rule to prioritize amongst multiple targets. LAMDA

simulations are deterministic given ABL and target altitudes, ranges, and the azimuth angle between them.

In its benchmarking approach, Boeing uses ABLPROP to generate irradiance and spot size vs. range and altitude for the ABL. LAMDA then combines vulnerability data with irradiance and spot size. From the ABLPROP results, EADSIM power propagation tables are generated for the fluence lethality mode (refer to the Lethality Determination Options section of Chapter 3). Using an ABL representation in EADSIM, a scenario identical to that from LAMDA is run in EADSIM. Results are compared, and the EADSIM propagation table is adjusted so that EADSIM output closely matches LAMDA output.

The metrics compared were the number of missiles killed and magazine usage (laser fuel expended). Differences in results from LAMDA and unadjusted EADSIM runs are attributed to the methods each model uses to determine spot size. EADSIM uses a Gaussian spot approximation, whereas LAMDA's calculations are more complex. Boeing representatives feel the calculations from LAMDA are more accurate.

Cross Resolution Model Connection

Current model building practices result in many independent models with different but overlapping resolutions. Integrating or using multiple models together is difficult because of differences in perspectives, assumptions, and definitions. Tying models together may not be efficient and can create problems with understanding model results (Davis, 1995:6). The term variable resolution model applies to the design of new models and allows users to rapidly change the resolution at which phenomena are treated.

More applicable for this effort is a similar concept called cross resolution model connection. Cross resolution model connection is a term used to describe the process of combining models of different resolutions designed to be used independently (Davis, 1995:6). The use of cross resolution modeling is based on many of the concepts of variable resolution modeling.

One example of the need to vary resolution is the use of higher resolution models to carry out special processes in a lower resolution model. Another possible use is the need to employ higher resolution to establish bounds for parametric analyses in lower resolution models (Davis, 1995:10).

Aggregation.

Military forces are normally comprised of a mixture of units in varying numbers. Mixing units is useful to reduce individual unit weaknesses or because of unit dependencies on other units. In combat models, aggregated descriptions of a mixed force are normally accomplished by using a single measure such as a "strength" or firepower "score" (Hillestad and Juncosa, 1995:37-8).

Sometimes such mixed force aggregation is accomplished by summing the values for each individual unit as is done in the Weapon Effectiveness Indices/Weighted Unit Values (WEI/WUV) approach (Hillestad and Juncosa, 1995:38). A more recent approach, called Situation Adjusted Scores, places value on the situations of combat. Yet another aggregation scheme, the Quantified Judgment Model of Dupuy, assigns a force score based on the situation and data from historical battles (Hillestad and Juncosa, 1995:39). Hillestad emphasizes, "the value of a force should depend strongly on the opponent and the situation."

Using the results of a mixed force in a simulated battle to predict the outcome of another battle adds extra uncertainty. Because different components of the force may survive any given conflict, the force mix after a single battle requires disaggregation to resolve. The result is a one-to-many mapping requiring more information than a single engagement to continue the simulation (Hillestad and Juncosa, 1995:40). Determination of force survival requires disaggregation.

There are two widely accepted methods of disaggregation of results. One method applies losses uniformly over the force, while the other method accounts for differing unit survivability measures. The uniform application of losses assumes each unit type sustains losses equal to the overall loss rate. The second method assigns losses proportionately to unit weakness (Hillestad and Juncosa, 1995:41-2).

Measures of Effectiveness.

A measure of evaluation of military forces should encompass all critical dimensions of the military environment. Though a single measure may not be an adequate predictor of outcome, an analyst may use a criterion to represents the influential factors of possible outcome. Such criteria are called Measures of Effectiveness (MOE) (Battilega and Grange, 1984:38-9).

In missile defense studies, there are a number of reasonable MOEs. Some important MOEs in APL's study are the number of missiles engaged, the number of missiles killed, and the area of defensive coverage provided by the anti-missile assets. Similarly, an MOE used in Boeing's work with LAMDA is the fraction of TBMs killed during the course of a campaign.

Summary

The DoD uses a variety of models encompassing several different levels of detail. At the mission level, a dominant model is EADSIM. Several missile defense studies have been accomplished using EADSIM, one of which uses the ABL. THUNDER is the Air Force's selected model at the campaign level. The results of EADSIM may be useful for THUNDER if taking care in the selection of appropriate MOEs and methods of aggregation.

3. Methodology

Overview

This research is accomplished in two parts. First, and mainly, EADSIM capabilities to model a tactical HEL weapon platform like the ATL are analyzed. Secondly, this effort offers a study of possible aggregation of mission level model information and data transfer opportunities for inclusion in the THUNDER campaign model.

To study EADSIM's treatment of an ATL platform, a notional scenario is constructed based on desired weapon capabilities from the ACTD program (Advanced, 2002), but with an expanded mission of greater interest to the JTO HEL to demonstrate ATL possibilities. Representations of the entities required for the scenario are then created or modified in EADSIM for use in the scenario. Using a designed experiment, simulation runs are made. The results support an analysis of alternatives.

Reports generated by EADSIM after each simulation run are considered the output of the simulation experiment. Using information presented explicitly on the reports, or with the help of creative manipulation of limited data, an assessment is made of the suitability and potential for aggregation of EADSIM output into THUNDER. All simulation runs use the same general scenario.

Simulation Scenario

The scenario used in this effort employs a single ATL platform to defend a friendly airfield against a salvo of cruise missiles.

Scenario Description.

The ATL is based on a C-130 Hercules aircraft carrying a HEL weapon mounted under its centerline. An important assumption is an unrestricted slew rate, or the rate at which the laser weapon may rotate to engage a target. Said another way, the laser weapon may rotate as quickly as necessary to place and maintain lethal energy on the target. Additionally, the laser weapon is assumed to be able to irradiate targets in a 360˚ field of engagement. The ATL flies an established circular pattern centered on latitude 29.5˚ N and 47.55˚E with a radius of 5 kilometers (km). The pattern is at an altitude of 15000 meters (m) and a velocity of 150 nautical miles per hour (knots).

The targets for the ATL, cruise missiles, will be launched in a nine missile salvo. The cruise missiles will appear in a wide area of launch susceptibility. The cruise missiles will fly at 100 m above ground level (AGL) at a speed of 400 knots. Their flight paths will be on course 180, or due south, until a predetermined waypoint is reach. At that time, the missiles will begin maneuvers to attack the friendly airfield, their target.

Target detection is not of interest in this research, primarily because target detection by sensors in EADSIM is subject to variability in time and location of first detection. To eliminate this variable, the field of view for the simulated radar is set to 360˚ and the detection range is set to greatly exceed the effective engagement distance of the ATL's laser weapon.

Scenario Randomization.

In the scenario, there are multiple model parameters set at randomly selected values. For example, the position of each of the nine cruise missiles upon launch from

the susceptible area is random. The position of the ATL in its circular orbit upon missile launch is also randomized. Also, the ATL's prioritization methodology of engaging multiple targets is changed across multiple runs. Finally, the laser weapon's jitter is varied. The following is a description of the parameters that were varied and their associated levels:

Target latitude: latitude of cruise missile launch
- Generated by Arena® model shown in Appendix A
- ~ Uniform (29.8, 29.97) stream 1

Target longitude: longitude of cruise missile launch
- Generated by Arena® model shown in Appendix A
- ~ Uniform (47.35, 47.75) stream 2

Cruise missile launch time
- Generated by Arena® model shown in Appendix A
- ~ Uniform (0, 420) stream 3

Threat prioritization: order in which ATL attacks multiple targets
- Randomly assigned
- Track maturity
- Longest time to kill
- Shortest time to kill

Jitter: a measure of beam spread resulting from vibration at source
- Randomly assigned
- 0% jitter
- 5x spot size jitter

Because several parameters are varied in the multiple runs of the simulation study, the assignment of the levels of the parameters for each simulation run is accomplished by randomization. Each combination of levels is called a treatment. The design of experiments function in JMP® is used to randomize threat prioritization in nine simulation runs with 0% jitter. The levels for target latitude, longitude, and launch time are randomly generated and assigned. Each treatment is replicated five times. The experiment is then duplicated with 5x spot size jitter.

The random number seed for each simulation run is set by the user. Run number one begins with seed 1. Each subsequent replication uses the final random number seed from the previous replication. The random number seed for the first simulation run of the next treatment is 1,000,000. The random number seed for following treatments is incremented by 1,000,000 over the previous treatment. Because EADSIM uses possible random number seeds from 1 to 4,294,967,295, all simulation runs may be completed without fear of exhausting the seeds (EADSIM User's Reference, 2000:6-4).

The randomization scheme for the nine run simulation experiment is shown in Table 3.1. The second waypoint for each target (the next waypoint after launch) uses the same longitude as the originating waypoint but latitude of 29.3. The same randomization scheme is duplicated with the change in the value for jitter.

Table 3. 1 Scenario Treatments

PARAMETER	TREATMENT NUMBER								
	1, 10	2, 11	3, 12	4, 13	5, 14	6, 15	7, 16	8, 17	9, 18
Target 1 Lat	29.821	29.845	29.813	29.866	29.916	29.826	29.93	29.964	29.869
Target 1 Long	47.653	47.713	47.435	47.511	47.558	47.6	47.54	47.586	47.371
Target 2 Lat	29.813	29.8	29.877	29.904	29.945	29.936	29.967	29.959	29.916
Target 2 Long	47.717	47.701	47.62	47.385	47.492	47.739	47.371	47.694	47.384
Target 3 Lat	29.844	29.899	29.895	29.937	29.866	29.883	29.941	29.829	29.966
Target 3 Long	47.504	47.479	47.684	47.694	47.468	47.368	47.674	47.54	47.718
Target 4 Lat	29.885	29.822	29.909	29.928	29.821	29.956	29.94	29.951	29.925
Target 4 Long	47.358	47.387	47.531	47.519	47.625	47.671	47.579	47.509	47.414
Target 5 Lat	29.96	29.906	29.952	29.868	29.919	29.954	29.941	29.926	29.856
Target 5 Long	47.373	47.67	47.546	47.355	47.649	47.403	47.382	47.39	47.516
Target 6 Lat	29.913	29.87	29.921	29.958	29.849	29.941	29.927	29.851	29.839
Target 6 Long	47.442	47.699	47.665	47.385	47.58	47.703	47.417	47.387	47.671
Target 7 Lat	29.884	29.928	29.886	29.965	29.842	29.881	29.914	29.932	29.957
Target 7 Long	47.372	47.39	47.592	47.572	47.734	47.655	47.421	47.478	47.358
Target 8 Lat	29.871	29.876	29.859	29.83	29.839	29.892	29.806	29.81	29.866
Target 8 Long	47.514	47.609	47.594	47.602	47.61	47.73	47.572	47.687	47.506
Target 9 Lat	29.921	29.847	29.828	29.882	29.962	29.867	29.86	29.943	29.886
Target 9 Long	47.61	47.534	47.7	47.547	47.496	47.47	47.546	47.547	47.585
Priority	Mature	Mature	Long	Long	Short	Short	Short	Mature	Long
Launch Time (s)	306	163	111	332	73	231	28	289	205

EADSIM Scenario Construction

The EADSIM architecture is designed to accomplish three major functions: scenario setup, scenario execution, and post-processing and analysis (Exec summary). The majority of user input is required in scenario setup, and particularly, in scenario generation. The application for scenario generation allows the user to create and specify all the components and parameters required for EADSIM to run a scenario.

EADSIM Data Types.

Data used by EADSIM is organized in a hierarchical manner as shown in Figure 3.1, which is Figure 5.1 from the EADSIM v9.00 User's Manual. As a brief introduction, the smallest level of the hierarchy is the *elements* data type. By aggregating elements, a *system* data type is formed. In the context of a scenario, a system is deployed as a *platform*. A collection of all deployed platforms forms a *laydown*. Each data type is explained in greater detail. (EADSIM User's Manual, 2000:Ch. 5)

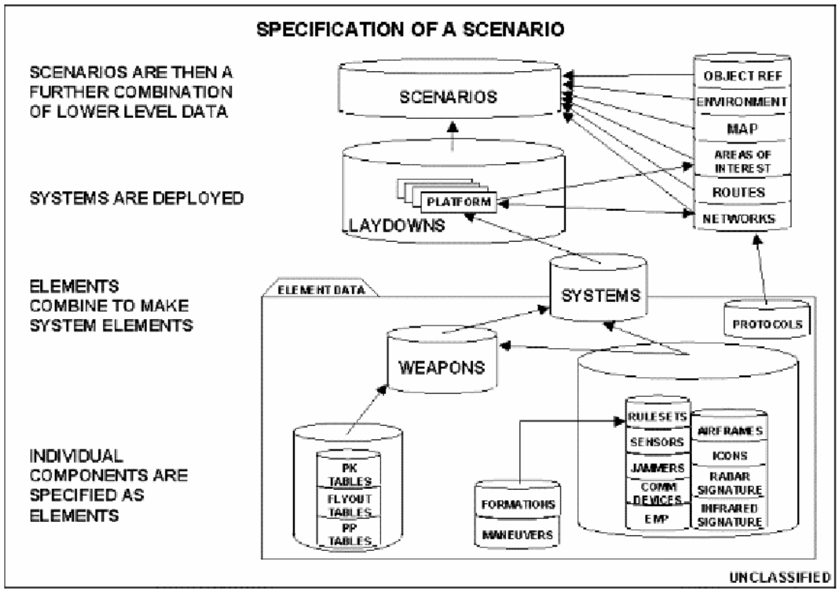

Figure 3. 1 EADSIM Data Structure

Elements.

Though there are numerous elements available, the four used for this effort are discussed. They include Airframe, Sensor, Weapon, and Ruleset. Other elements were not used because of their irrelevance in the scenario selected for this effort.

The Airframe element allows the user to model an airborne vehicle such as a fixed-wing aircraft, helicopter, or missile. The user establishes the available parameters to describe the airframe such as speeds, weights, and acceleration tolerances. Sensor elements model various radars, infrared sensors, and intelligence gathering receivers. They may be modified by users to represent different fields of view, sweep rates, antenna parameters, and other important sensor characteristics. EADSIM's Weapon elements are used to describe guided and unguided bombs, missiles, lasers, and other types of weapons. Important parameters adjustable by the user include guidance, reliability,

launch and intercept constraints, and lethality. The behavior of a system is defined in EADSIM by the Ruleset element. Rulesets dictate what a system can or will do when being engaged by enemy forces or having to classify potential targets.

Systems.

After all required elements have been modified or created, the user may assemble a system. System assembly is done via the System Definition Window shown in Fig 3.2, which is Fig 5-12 from the EADSIM v9.00 User's Manual.

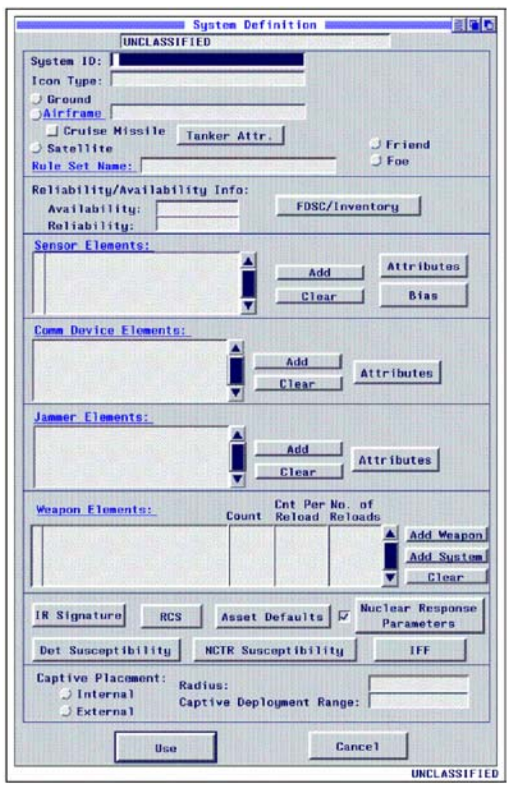

Figure 3. 2 System Definition Window

This window allows the user to take such actions as assign Airframe, Sensor, Weapon, and Ruleset elements, as well as specify an icon for the post processing viewer. Other actions include defining the infrared and radar cross-section signature of the system. A fully assembled and specified system is not available to the user in an EADSIM scenario until it is deployed as a platform.

Platforms.

Deploying a platform is accomplished by opening the Deploy Platform Window shown in Fig 3.3, Fig 5-25 from the EADSIM v9.00 User's Manual.

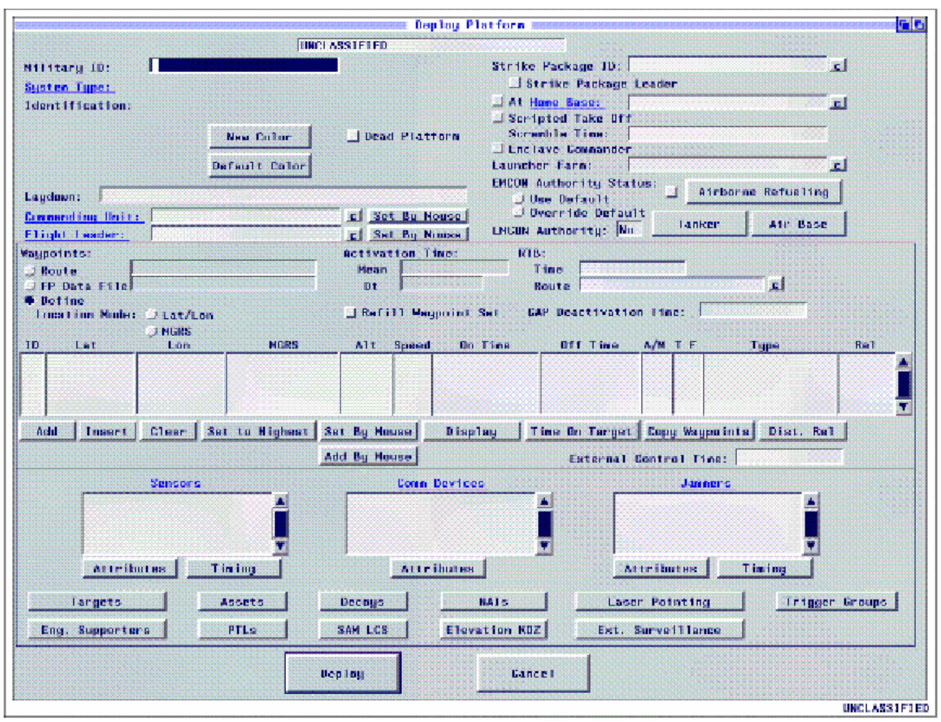

Figure 3. 3 Deploy Platform Window

The user must assign a Military ID, which will be used to identify the platform in the scenario and associated output. This window is also used to establish a platform's chain of command by stipulating the platform's flight leader (if an airborne asset flying as part of a unit) and commanding unit. A route file or user defined waypoints, which may be placed directly on the scenario map, define the platform's route. The Deploy Platform Window may also allow alteration of several parameters such as a Sensor's operational attributes. Some systems with the ability to attack may allow the user to generate a list of targets. Unfortunately, this option is not available for laser systems.

Laydowns.

According to the EADSIM v9.00 User's Manual, a laydown "is a file which contains a specified group of deployed platforms." Once a laydown is created, users may only rename the laydown or adjust the times the laydown becomes active on the scenario map.

Laser Ruleset.

An engagement using laser weapons in EADSIM v9.00b is carried out in two phases identified as Laser Battle Management Phases. The first phase, called the target selection phase, includes threat assessment and the selection of the laser weapon which will engage a target. The launch/lase phase is the second battle management phase (EADSIM Methodology Manual, 2000:4-306). A diagram of the entire process is shown in Figure 3.4, taken from Figure 4.35 of the EADSIM v9.00 Methodology Manual.

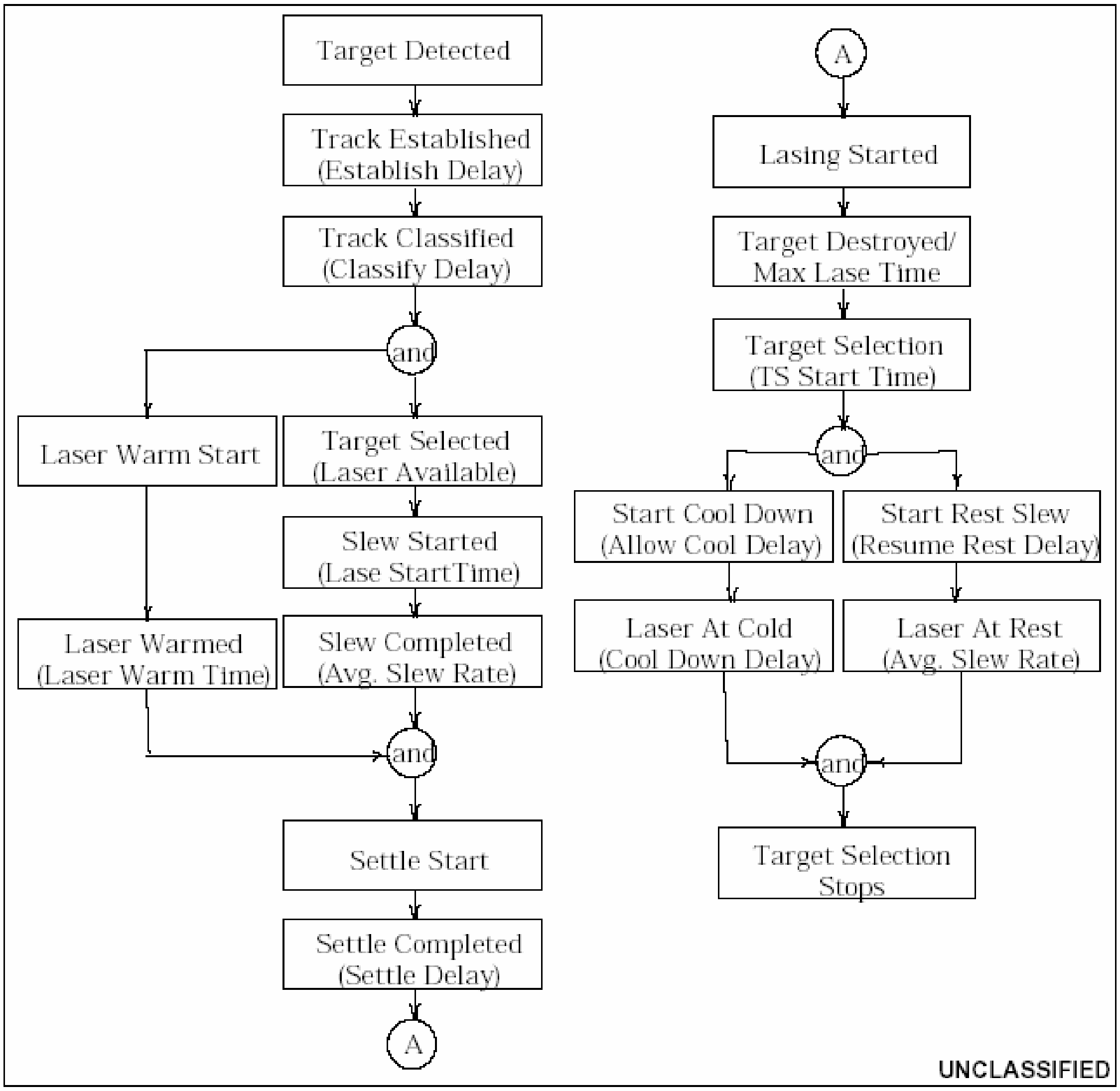

Figure 3. 4 Laser Engagement Process

In the scenario used for this research, which is described previously in this chapter, the laser platform of interest, an ATL, is autonomous. In other words, the ATL in the simulation does not receive guidance or instruction from any command structure and may freely engage targets. Therefore, according to the EADSIM v9.00 Methodology

Manual, the ATL's target select phase for the scenario described will not begin until an entry is made in the ATL's track file. (EADSIM Methodology Manual, 2000:4-306)

Target Selection Phase.

In EADSIM, a track is created when either one platform detects another entity or is made aware by notification from another entity and the platform tracks it, or updates the position of the entity with time (EADSIM Methodology Manual, 2000:4-1). Tracks may be created for unknown, hostile, and friendly entities. Once a platform begins tracking another entity, entries are made in the platform's track file. Information about all tracks being monitored by a platform is placed in a track file (EADSIM Methodology Manuel, 2000:4-20).

When a track file is updated with a new track, the target-select phase is initiated. The first process within this phase is threat assessment (EADSIM Methodology Manual, 2000:4-306). When an entity is classified as a threat, threat assessment is accomplished by determining which hostile tracks are to be engaged, determining which targets may be engaged under the parameters specified in the laser ruleset, and prioritizing threats for the laser to target assignment if multiple tracks exist (EADSIM Methodology Manual, 2000:4-309).

The second process within the target-selection phase is the laser-to-target assignment, or weapon selection process (EADSIM Methodology Manual, 2000:4-306). EADSIM plans the amount of time a platform requires to kill a target. This is done by accounting for delays such as laser warm-up from an inactive state, if necessary, slewing the laser toward the target, and calculating a planned time to kill. For a detailed

discussion of how EADSIM calculates a planned time to kill, the reader is directed to pages 4-317 through 4-320 of the EADSIM version 9.00 Methodology Manual.

Launch/Lase Phase.

The launch/lase phase models the activity of the platform from the moment the decision to engage the target is made through the endgame determination. If the target is determined to be friendly, or if the platform cannot maintain a local sensor track, the engagement is aborted (EADSIM Methodology Manual, 2000:4-321, 4-322).

The platform's laser activities in this phase are slewing, warming, settling, and lasing. The term slewing is used to describe unstowing the laser from a stowed configuration and orienting it toward the target (EADSIM Methodology Manual, 2000:4-322). EADSIM models simple laser slewing with a delay as a function of the angle between the direction in which the laser is currently pointing and the required direction and the slew rate of the laser as described in Section 4.7.33.6.1 of the EADSIM v9.00 Methodology Manual. The laser requires a warmup period, modeled as a delay in EADSIM, to heat up in preparation of actual lasing. Once the laser is slewed and warmed, a settle delay is assessed to model such functions as control system dampening or optical measurements (EADSIM Methodology Manual, 2000:4-323). The final activity is lasing, or the placement of lethal energy on target (EADSIM Methodology Manual, 2000:4-324). The endgame is decided through lethality determination.

Lethality Determination Options.

EADSIM v9.00b offers four ways to assess lethality; shared object, ISAAC, intensity based, and fluence based (EADSIM Methodology Manual, 2000:4-326). The

shared object model allows the user to develop an algorithm to resolve laser engagements. The complexity of development and use of this method of lethality determination was beyond the scope of this effort. ISAAC was not used because it is a proprietary model of the Schafer Corporation and its use in EADSIM is designed for an ABL vs. ballistic missile engagement (Burckel, 2002).

The fluence methodology uses the amount of energy deposited on a target as a means of assessing a kill. By identifying the constant intensity of a beam placed on target and the length of time the beam irradiates the target, a total amount of energy placed on target may be calculated. By using a single uniform random draw compared against a single probability of kill (P_k) or a P_k curve, a kill determination is made (EADSIM Methodology Manual, 2000:4-327-28). Because the scenario described uses a moving laser weapon and moving targets, the assumption under the fluence methodology of a constant intensity beam is questionable. As a result the intensity based methodology is used.

Intensity Based Methodology.

The intensity based methodology uses laser intensity on the target, which may be accumulated under different clock cycles and corrected for changes in beam intensity as a result of changing propagation circumstances, to resolve a laser engagement. EADSIM's description of laser beam intensity placed on the target at a given time is a function of peak intensity and beam spread. These parameters are read from a lookup table called a power propagation table (EADSIM Methodology Manual, 2000:4-328). Next, a random number draw from a Uniform (0,1) distribution is used to establish a target's level of

survivability. In other words, the draw places a particular target in the x^{th} percentile of survivability for all targets of that type (EADSIM Methodology Manual, 2000:4-326).

Using the peak intensity on target, read from the propagation table, and the uniform random number draw, a comparison is made to vulnerability data, which will determine the dwell time, or the amount of time lethal energy must be placed on the target. Because the lethal energy may be placed over several clock cycles which may change the laser parameters, a partial kill fraction is accumulated. When the total fractional kill accumulates to the appropriate level, the target is assumed to be destroyed (EADSIM Methodology Manual, 2000:4-328).

Though there may be many points on a cruise missile target which may be vulnerable to laser energy, EADSIM reduces such points, called aimpoints because the laser is aimed to irradiate them, to a set of three. The aimpoints used by EADSIM are the nose, the fuselage, and the wing. Each may be specified to have unique vulnerability parameters.

Propagation Table Generation.

EADSIM allows a power propagation table to be indexed by the following variables (EADSIM Methodology Manual, 2000:4-330-1):

- Weapon altitude: altitude in kilometers (km) of laser platform in Mean Sea Level (MSL)
- Target altitude: target altitude in km relative to weapon altitude*
- Target range: range in km from laser to target
- Target NADIR: angle in degrees between point beneath laser and zenith
- Target perpendicular velocity: relative perpendicular velocity in meters per second (m/s) between laser and target
- Target azimuth: angle in degrees between laser platform orientation and target
- Target AGL: altitude in km of target above ground level (AGL)

- Total lase time: amount of time in seconds lase has been continuously depositing energy. Used for cases of laser degradation over time

* Though the EADSIM Methodology Manual states target altitude is relative to Means Sea Level (MSL), in practice it is relative to the laser weapon.

For this effort, the propagation table is indexed by target range. The fundamental equation for the propagation table is the brightness equation, a first-order approximation of propagation. The result is a magnitude of intensity propagated through an atmosphere under specific conditions. Based on Tyson's definition (Tyson, 1998:24),

$$B \approx \left\{ \frac{\pi D^2 P}{4\lambda^2} \right\} \left\{ e^{-\left(\frac{2\pi\omega}{\lambda}\right)^2} \right\} \left\{ \frac{1}{1 + \frac{\pi^2}{2}\left(\frac{j}{\lambda / D}\right)^2} \right\} \tau \tag{1}$$

where B = Brightness (watts / steradian)

D = Diameter of transmitting aperture (meters)

P = Power of laser (Watts)

λ = Wavelength (meters)

ω = Wavefront error (root mean square as percent of λ)

j = Jitter (root mean square as a percent of λ / D)

τ = Transmission of atmosphere (percent)

Two propagation tables are generated. The first is for the case of no jitter but with a mild wavefront error of 0.2 times the wavelength. The second table simulates a factor for jitter of 2.205 * λ to describe conditions of vibration and other motion on the laser platform which would cause the expected incident laser beam spot size to be five times larger than the case with no jitter. The variables used for the brightness equation are shown in Table 3.2.

Table 3. 2 Brightness Equation Inputs

Variable	Value
D	1 m
P	50000 Watts
λ	1.315×10^{-6} m
ω	0.2 x λ
j	0 / 2.205 * λ
τ	0.9

The values used in the propagation tables, as implemented in the simulation runs, appear in Appendix B.

Since the magnitude of brightness is independent of range, the distance from the target to the source must be accounted. To accomplish this, a conversion to radiant flux density indexed by range is performed, which generates an intensity measure on a normal plane on the target at a specified range.

$$Rad = \frac{B}{R^2} \qquad (2)$$

where Rad = Radiant Flux Density (watts / m^2)

B = Brightness (watts / steradian) from (1)

R = Vector range from target to source (meters)

To account for the effect of varying angles of incident beams on the source, an incident angle is calculated. The irradiance on a target is then corrected according to the

size of that angle. EADSIM accomplishes this by, first, calculating a vector from the laser to the target (EADSIM Methodology Manual, 2000:4-318-19).

$$\vec{R} = \vec{P}_T - \vec{P}_L \tag{3}$$

where $\vec{R}$ = Vector from laser to target

$\vec{P}_T$ = Target position

$\vec{P}_L$ = Laser position

Next, the angle of incidence is computed based on the particular target aimpoint. For the nose,

$$A = \left| \frac{\vec{V}_T \bullet \vec{R}}{\left|\vec{V}_T\right|\left|\vec{R}\right|} \right| \tag{4}$$

where A = Index of incidence on the target

$\vec{V}_T$ = Velocity vector of target

$\vec{R}$ = Vector from laser to target from (3)

If the angle of incidence on the nose is less than or equal to 0, then the angle of incidence on the nose is:

$$\theta_N = 90° \tag{5a}$$

else,

$$\theta_N = \cos^{-1}(A) \tag{5b}$$

The angle of incidence on the fuselage is calculated as,

$$\theta_F = 90° - \cos^{-1}(A) \tag{6}$$

To determine the angle of incidence to the wing, the calculation for A is altered so the vector position of the target is substituted for the vector velocity of the target.

$$A_w = \left| \frac{\vec{P}_T \bullet \vec{R}}{\left|\vec{P}_T\right| \left|\vec{R}\right|} \right| \tag{7}$$

The angle of incidence is then calculated by,

$$\theta_W = \cos^{-1}(A_w) \tag{8}$$

After calculating the angle of incidence for the appropriate aimpoints, EADSIM adjusts the intensity incident on the target using the following equation (EADSIM Methodology Manual, 2000:4-319):

$$I = I_{peak} \times \cos(\theta) \tag{9}$$

where I = Peak intensity at specified aimpoint

I_{peak} = Peak intensity at target normal to beam (Watts / cm^2)

θ = Incident angle at aimpoint

Vulnerability Table Generation.

To construct a lookup table for vulnerability, a decision about kill method is required. According to Ng (2001:27), the most common method to destroy an anti-ship cruise missile is weakening the structure of the missile body. He identifies damaging flight controls as another possible kill mode. This research assumes weakening of the structure at any of the three aimpoints used by EADSIM, nose, fuselage, or wing, will cause a catastrophic failure or destruction of the missile so it may not complete its assigned mission.

The next assumption to establish target vulnerability is the construction material and thickness of a target. A damage study done at the Naval Postgraduate School (NPS) uses a target made of aluminum with three layers, each of 1 cm thickness (McGinnis and others, 2000:4). The NPS study further suggests one way to assess the energy required to destroy such a target is to calculate the amount of energy required to vaporize a target with the specified parameters (McGinnis and others, 2000:5).

According to McGinnis (McGinnis and others, 2000:5), the energy required to vaporize a material may be calculated from the following equation:

$$E_0 = \rho d\left(C\left[T_m - T_0\right] + \Delta H_m + C\left[T_v - T_m\right] + \Delta H_v\right) \qquad (10)$$

where E_0 = Flux density (Joules / m^2)

ρ = Material density (kg / m^2)

d = Material thickness (m)

C = Specific heat capacity (Joules / kg · ˚C)

T_m = Melting temperature (˚C)

T_0 = Ambient temperature (˚C)

T_v = Vaporization temperature (˚C)

ΔH_m = Latent heat of fusion (Joules / kg)

ΔH_v = Latent heat of vaporization (Joules / kg)

Using target thickness of 3 cm, an ambient temperature of 25 ˚C, and the material properties for aluminum shown in Table 3.3 (Serway, 1996), the required flux density to destroy the target is calculated in equation (11).

Table 3. 3 Aluminum Properties

Melting temperature	660 ˚C
Vaporization temperature	2450 ˚C
Density	2.7 x 10^3 kg / m^3
Specific heat capacity	900 J / kg ˚C
Latent heat of fusion	3.97 x 10^5 J / kg
Latent heat of vaporization	1.14 x 10^7 J / kg

$$E_0 = 1.132 \times 10^5 \, J / cm^2 \tag{11}$$

Ng (28) notes that absorption (the rate at which a material absorbs energy) varies by material and beam type. For instance, light colored painted metals have an absorption rate of 35% when irradiated by ruby laser light. The absorption rate for the same surface is 95% for a CO_2 laser. To account for less than ideal material absorption properties of the target, the required flux density used in the model is adjusted to twice the value shown in equation (11). This is equivalent to assuming the cruise missile target absorbs 50% of the incident ATL energy.

By dividing the energy required for vaporization by the radiant flux density which can be placed on the target, the required dwell time, T_d, to kill the target is estimated.

$$T_d = \frac{E_0}{Rad} \tag{12}$$

This estimation requires the assumption that laser energy is delivered at a much greater rate than the thermal diffusivity of the target allows the energy to be dissipated.

To account for variation in survivability, the vulnerability table is indexed for the 50^{th}, 70^{th}, 80^{th}, and 90^{th} percentile. The dwell times calculated by the preceding equations are used to populate dwell times at the 50^{th} percentile. The 70^{th} percentile uses dwell times 10% longer than those of the 50^{th} percentile. The 80^{th} and 90^{th} percentile use dwell time values 20% and 30% longer, respectively, than those of the 50^{th} percentile. Percentiles greater than 90% are modeled as indestructible by stipulating a dwell time longer than the specified longest shot time of 180 seconds, thus adding a possibility of an engagement without a kill. The table values, as used in the scenario described, may be found in Appendix C.

Intensity Based Lethality Example.

A brief example may be useful to illustrate the process EADSIM uses to resolve an engagement with the intensity based methodology in the scenario discussed. Readers familiar with EADSIM's intensity based lethality model or with a clear understanding of the process should proceed to the next section.

Consider an ATL platform which has classified a cruise missile as a threat, established a track for the missile, and made the decision to engage. After EADSIM advances the simulation to account for the time delay incurred due to laser warm-up, slewing, and settling, the placement of lethal energy is simulated. EADSIM determines the range from the ATL to the target missile. Peak intensity is read from the propagation lookup table, which is indexed by range. This intensity is degraded by the cosine of the incidence angle to determine the peak intensity at the specified aimpoint. Also, the survivability of the target is decided by a uniform random number draw. EADSIM again

uses a lookup table, vulnerability in this case, to determine the dwell time required to kill the target with the calculated incident intensity and the randomly drawn survivability level. For instances where the dwell time exceeds the simulation cycle time, a partial kill is accumulated for the time elapsed during the cycle, and the process repeats for the next simulation cycle. The process continues until the target is killed or the maximum energy to be placed on target is exceeded.

EADSIM File Modifications.

To create the scenario used in this research, several EADSIM elements were created. In the interest of reproducibility of this effort, details about the basis for each new data type and variations in the respective parameters may be found in Appendix D.

Measures of Effectiveness

The measures of effectiveness used in this effort are limited by the output generated in EADSIM's reports. The two measures of effectiveness are the fraction of targets killed and total laser firing time.

As variables are changed, the fraction of target kills is expected to be affected. Examining the number of kills will illustrate the effectiveness of the ATL using given parameters. Because one of the variables is target prioritization, this MOE may illuminate which tactic the ATL should employ for greatest success against a cruise missile target.

Total laser firing time is a measure of how long the ATL must place lethal energy on the target. This MOE will explore how much laser fuel may be expended during an

engagement with cruise missile targets. The end result may be used to plan the laser fuel loading on the ATL for a desired engagement size.

THUNDER Inputs

The ATL scenario in this effort best matches the role of Barrier Combat Air Patrol (BARCAP). (THUNDER Methodology, 30). The BARCAP mission describes an airborne anti-air asset patrolling an area and intercepting enemy aircraft which enter its area of responsibility. When a target enters the patrolled zone, a determination of detection is made based on a calculated detection probability depending mostly on the area of the patrolled zone and the sweep area of the sensor. If detection occurs, an engagement is resolved (THUNDER Methodology, 46-48)

THUNDER creates a composite measure to describe the type of weapons and their associated capabilities for the attacking platform. Next, a determination of range advantage is made if the attacker or defender possesses weapons with longer range. Then, an engagement probability is used (THUNDER Methodology, 50-53).

Engagement probability is a measure of the likelihood a platform can engage a target. The probability comes from an input file (detect.dat) which accounts for such factors as sensor effectiveness, cockpit visibility, and platform maneuvering capability (THUNDER Methodology, 54). In addition to engagement probability, shooter survivability is calculated based on the fraction of time a shooter's weapon has a range advantage and the probability the shooter is able to engage the target. Shooter survivability is used to determine the availability of a platform to carry out an attack and the probability of the

shooter launching. If an attack proceeds, THUNDER uses a single shot probability of kill. Single shot probability of kill is defined by,

$$SSPK_{attac\,\mathrm{ker}\,vsdefender} = Pl_{shooter} * Pk_{shooterweaponvsdefender} \tag{13}$$

where $Pl_{shooter}$ = Probability of launch

$Pk_{shooterweaponvsdefender}$ = Probability of kill of weapon against defender

Notably, $Pk_{shooterweaponvsdefender}$ is read from an input file labeled airairpk.dat (THUNDER Meth 50-58).

Summary

A notional ATL cruise missile defense scenario is created in EADSIM to assess potential treatment of the ATL in a mission level model. The details of the scenario construction were outlined in this chapter with greater detail about the elements used being available in Appendix D. The cruise missile launch locations and ATL orbit position are assigned randomly. The ATL's target prioritization methodology is varied as are the laser propagation values to conduct a simulation experiment. The MOEs are the number of targets killed and the amount of time the laser fires during an engagement.

This chapter also explained the creation of the propagation and vulnerability tables and provided an example tracing the resolution of a laser engagement in EADSIM. In Chapter 4, the results of EADSIM are analyzed to determine if target prioritization and laser propagation values are significant factors in the model. Further, the outputs of EADSIM are assessed for aggregation as potential input data for THUNDER.

4. Results

Overview

This chapter explains the results of statistical analysis of the simulation experiment output provided in Appendix E. The two primary tools used are ANOVA and linear regression. Difficulties and shortcomings of the use of these tools in this experiment are discussed. The analysis is extended to additional simulation runs performed to exploit factors of opportunity not considered by the author during the development of the experimental methodology.

Numerical Analysis

As explained in Chapter 3, the parameters varied in the simulation are target prioritization and the measure of jitter affecting laser beam propagation. Cruise missile launch time and location are randomized throughout the scenarios. While all parameters may be candidates to become factors, consider the assignment of levels to each. Because the combination of cruise missile launch times and locations are stipulated together in the creation of one of nine EADSIM scenarios, the effect of launch time and the effect of launch locations on simulation output may not be discerned from each other. The effects are said to be aliased. However, by defining scenario number as a factor, information about the effect of both parameters together may be gleaned. Hence, the factors to be evaluated are Priority, Scenario, and Jitter. The results of the one-way ANOVA comparisons performed in JMP® are shown for the factors Priority, Scenario, and Jitter in Tables 4.1-3.

Table 4. 1 ANOVA of Priority (all data)

Source	DF	Sum of Squares	Mean Square	F Ratio
Model	2	3.01111	1.50556	2.0674
Error	177	128.90000	0.72825	Prob > F
C. Total	179	131.91111		0.1296

Table 4. 2 ANOVA of Scenario (all data)

Source	DF	Sum of Squares	Mean Square	F Ratio
Model	8	21.71111	2.71389	4.2112
Error	171	110.20000	0.64444	Prob > F
C. Total	179	131.91111		0.0001

Table 4. 3 ANOVA of Jitter (all data)

Source	DF	Sum of Squares	Mean Square	F Ratio
Model	1	60.08889	60.0889	148.9208
Error	178	71.82222	0.4035	Prob > F
C. Total	179	131.91111		<.0001

The ANOVA of Priority reveals it is not a significant factor. Note the test statistic value of 2.0674 is less than the critical F value of 3.047 determined by 2 numerator degrees of freedom, 177 denominator degrees of freedom, and $\alpha=0.05$. Another way of determining the significance of the factor is to look at the value given for Prob > F. This value is analogous to a p-value, or the probability of finding an F value more extreme than the test statistic. Because this value is greater than $\alpha=0.05$, the output or result is considered statistically indifferent to the value of the factor. In contrast, the ANOVAs for Scenario and Jitter reveal both factors are significant.

The assumptions of normality of residuals, independence of data, and constant variance of residuals must be considered, and determinations about influential data points

and outliers must be made. In each case, independence was satisfied and outliers and influential data points deemed insignificant, however, normality and constant variance are questionable. The reason for the deviation from these assumptions may be attributed to the integer characteristic of the response variable, number of kills. To counter this effect, taking an average across multiple replications may be considered. However, the deterministic nature of the simulation, to be discussed later, negates the benefit. To be able to perform any analysis on the data, the assumptions of normality and constant variance must be relaxed. Relaxation of these assumptions is carried through to all other numerical analyses presented in this chapter.

Another option for data analysis is to perform an ANOVA using all of the factors and their interactions. Doing so reveals a shortage of degrees of freedom in the data caused by a flaw in the original experimental design. The assignment of a target priority to a particular scenario creates another alias. Separation of the effects of differences due to priority and the effects of differences due to scenarios is not possible. ANOVA of two or more factors in this case requires inclusion of either Scenario or Priority, but not both. The ANOVAs including the interaction of Scenario and Jitter and the interaction of Priority and Jitter are shown in Tables 4.4 and 4.5.

Table 4. 4 ANOVA w/ Scenario (all data)

Source	DF	Sum of Squares	Mean Square	F Ratio
Model	17	103.51111	6.08889	34.7324
Error	162	28.40000	0.17531	Prob > F
C. Total	179	131.91111		<.0001

Effect Tests

Source	Nparm	DF	Sum of Squares	F Ratio	Prob > F
Jitter	1	1	60.088889	342.7606	<.0001
Scenario	8	8	21.711111	15.4806	<.0001
Scenario*Jitter	8	8	21.711111	15.4806	<.0001

Table 4. 5 ANOVA w/ Priority (all data)

Source	DF	Sum of Squares	Mean Square	F Ratio
Model	5	66.11111	13.2222	34.9645
Error	174	65.80000	0.3782	Prob > F
C. Total	179	131.91111		<.0001

Effect Tests

Source	Nparm	DF	Sum of Squares	F Ratio	Prob > F
Priority	2	2	3.011111	3.9813	0.0204
Jitter	1	1	60.088889	158.8977	<.0001
Priority*Jitter	2	2	3.011111	3.9813	0.0204

In each case, the models are significant. With the inclusion of two or more factors, the effects test portion of the table is included to assess the significance of each effect. The values for the Prob > F cell in each table is less than $\alpha=0.05$, communicating the significance of all effects. Note that although Priority was not a significant factor in a one factor ANOVA, it is significant when considered with multiple effects.

One problem with the resultant simulation data is the number of zero values for the response variable, number of kills. Using a value of jitter which causes the laser beam spot size on the target to be five times larger than the spot size without jitter contributes to the number of zeroes in the data. In fact, no kills were recorded with the

range of parameters specified using a 5x jitter value. For completeness, the previous analysis is repeated excluding data points with zero values for the response variable. Tables 4.6 and 4.7 show the results of single factor ANOVAs for Priority and Scenario.

Table 4. 6 ANOVA of Priority (exclude zeroes)

Source	DF	Sum of Squares	Mean Square	F Ratio
Model	2	1.706667	0.853333	2.2143
Error	62	23.893333	0.385376	Prob > F
C. Total	64	25.600000		0.1178

Table 4. 7 ANOVA w/ Scenario (exclude zeroes)

Source	DF	Sum of Squares	Mean Square	F Ratio
Model	7	12.200000	1.74286	7.4136
Error	57	13.400000	0.23509	Prob > F
C. Total	64	25.600000		<.0001

The results of the one way ANOVAs excluding zero response values mimic those including all data. Again, Priority is not significant, while Scenario does have an effect on the output. Because all response values obtained using the 5x jitter parameter were zero, the effect of Jitter can't be examined.

Due to the aliasing of the factors Priority and Scenario and the number of response values at zero with the inclusion of jitter at a value to induce a spot size five times larger than the no jitter case, the analysis is limited. With the inclusion of one easily changed factor more analysis may be performed. Changing the altitude of the ATL from 4000 ft to 2000 ft offers more possibilities for analysis, but more simulation runs are required. After repeating all treatments with a low altitude setting, the response values obtained by including jitter were again zero. The ANOVA including Priority may not

include jitter. The analysis including Scenario is further restricted to factor effects only (no interactions) due to the limitation of degrees of freedom. After confirming the significance of the ANOVA, the significance of the effects is reported in Table 4.8 and 4.9.

Table 4. 8 Effects Test w/ Priority & Altitude

Source	Nparm	DF	Sum of Squares	F Ratio	Prob > F
Altitude	1	1	3.2438596	10.8949	0.0016
Priority	2	2	2.4655072	4.1404	0.0208
Priority*Altitude	2	2	4.0307246	6.7689	0.0023

Table 4. 9 Effects Test w/ Scenario & Altitude

Source	Nparm	DF	Sum of Squares	F Ratio	Prob > F
Scenario	7	7	14.980000	14.4734	<.0001
Altitude	1	1	5.120000	34.6280	<.0001

Note the significance of all effects. Priority is once again significant when considered with other factors. However, the limitation on the factors prohibits the predictive power of the model. Two new factors are included. The engagement azimuth is changed from 180˚ to 270˚ and 360˚. Also, the power of the laser is varied by changing another parameter in the model.

Any change in laser performance requires a new or modified propagation table. To eliminate this necessity, a substitution of variables may be performed. Recall from Chapter 3 the lethal fluence on a target is approximated by brightness, divided by the square of the range from ATL to target, and multiplied by the dwell time required for the kill. Power is a linear effect in the brightness equation, which in turn, along with time, is linear with respect to fluence. By slowing all moving entities in the simulation to half the

original speed, all targets spend exactly twice as much time in the engagement volume of the ATL. In other words, the ATL has exactly twice the time to irradiate a target and achieve a kill. By dividing an observed time, such as a time to kill, in half there is no net change in a recorded time due to slowing all entities to half speed, though a kill is achievable which would not otherwise be possible. By attributing this simulated doubling of fluence to a change in brightness, the level of power may be altered.

Time prohibited the full exploration of the design space, and only treatments of interest are simulated. Figure 4.1 shows points in the design space which were examined with all simulation runs, including those introduced with addition of the factors Azimuth and Power. The dots indicate design points studied. Though Scenario and Priority are not shown in the figure, all design points are replicated in each.

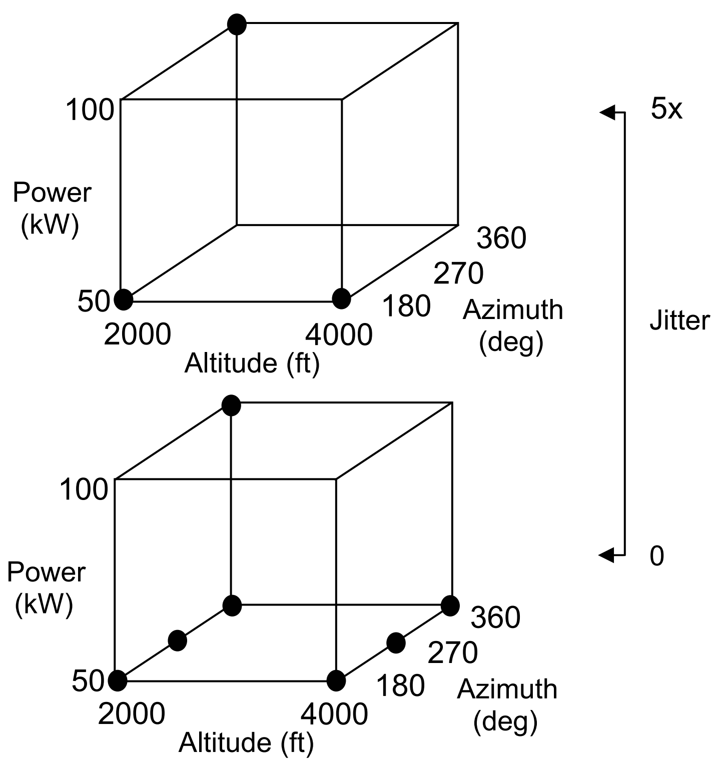

Figure 4. 1 Experimental Design Points

After performing one way ANOVAs on Scenario and Priority, both are confirmed to be significant. Choosing the factor Scenario and still excluding data points with zero valued responses, a multiple factor ANOVA is performed. In this case, Jitter is included, though limited degrees of freedom due to the large number of categorical variables and the limitation of design points prevents the inclusion of many interactions.

Table 4. 10 ANOVA w/ Scenario, Power, Azimuth

Source	DF	Sum of Squares	Mean Square	F Ratio
Model	12	294.99780	24.5832	92.9676
Error	289	76.41942	0.2644	Prob > F
C. Total	301	371.41722		<.0001

Effect Tests

Source	Nparm	DF	Sum of Squares	F Ratio	Prob > F
Altitude	1	1	9.459784	35.7746	<.0001
Jitter	1	1	93.035367	351.8376	<.0001
Azimuth	1	1	61.629796	233.0692	<.0001
Power	1	1	30.441618	115.1229	<.0001
Scenario	8	8	87.096555	41.1723	<.0001

The associated prediction profile plots provide visual clues about the effect of each factor on the response, number of missiles killed. These plots are shown in Figure 4.2.

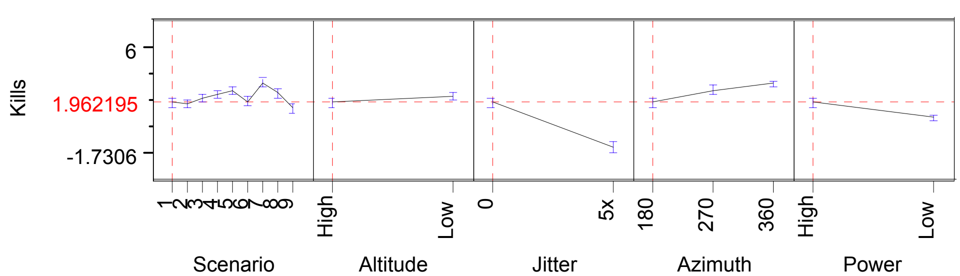

Figure 4. 2 Prediction Profile Plots

Intuitively, the effect of Scenario should be attributed to cruise missile launch time (or ATL orbit position), not cruise missile launch locations. The laser is capable of attacking targets at range, so location alone may not be a hindrance to an attack. However, the time a target spends in the volume of space in which the ATL may attack it, also known as the engagement volume, directly affects the opportunity for an ATL to attack a target. To quantify this intuitive assertion, an analysis of interest is whether the contribution of greater engagement azimuth, specifically 360˚, can overcome the effect of cruise missile launch time (ATL position).

Table 4. 11 ANOVA of Scenario & Azimuth

Source	DF	Sum of Squares	Mean Square	F Ratio
Model	17	191.70825	11.2770	17.8213
Error	284	179.70897	0.6328	Prob > F
C. Total	301	371.41722		<.0001

Effect Tests

Source	Nparm	DF	Sum of Squares	F Ratio	Prob > F
Scenario	8	8	79.449921	15.6947	<.0001
Azimuth	1	1	85.600916	135.2779	<.0001
Scenario*Azimuth	8	8	13.423889	2.6518	0.0081

Table 4.11 provides evidence that Scenario, Azimuth, and their interaction are significant. Hence, the position of the ATL in its orbit is not the only contributor to the factor Scenario. The locations of the cruise missile, isolated in the factor Scenario in this model, are also significant.

For the greatest predictive value, a linear regression technique is used. The construction of the linear regression model better quantifies the expected value of the response variable with respect to the factors included. To allow for the inclusion of some

two way interactions, Priority is used in lieu of Scenario. The regression results are shown in Table 4.12.

Table 4. 12 Full Model Regression Results

RSquare	0.662925
RSquare Adj	0.652535
Root Mean Square Error	0.654791
Mean of Response	2.516556
Observations (or Sum Wgts)	302

Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	2.6553648	0.056184	47.26	<.0001
Pri_Long[0]	0.023088	0.047438	0.49	0.6268
Pri_Shrt[0]	-0.322516	0.047438	-6.80	<.0001
Alt_Hi[0]	0.1820875	0.042138	4.32	<.0001
Az_270[0]	-0.392604	0.053856	-7.29	<.0001
Az_360[0]	-0.707609	0.058646	-12.07	<.0001
Pri_Long[0]*Az_360[0]	0.1466763	0.047438	3.09	0.0022
Pri_Shrt[0]*Az_360[0]	0.1650072	0.047438	3.48	0.0006
Pow_Hi	1.1401347	0.126757	8.99	<.0001
Jit_5x	-3.353248	0.216708	-15.47	<.0001

As a result of tricking the simulation into simulating double power by slowing all entities to half speed, all contributors in the brightness equation are aliased. For example, in the preceding results, the changes in fluence placed on target, which subsequently changed the response, were attributed solely to a change in power. However, a change in jitter will also cause a change in fluence placed on target. There exist multiple values for jitter and power such that the accumulated fluence is the same. By coding each combination of power and jitter into a normalized coded variable space valued from 0 to 1 and performing a linear regression, a predictive model may be created. The

combinations of power and jitter, which were encompassed in the design space, and their associated coded values are as follows:

- 50,000W, 5x jitter = 0.02
- 100,000W, 5x jitter = 0.04
- 50,000W, 0 jitter = 0.5
- 100,000W, 0 jitter = 1

The regression results are shown in Table 4.13.

Table 4. 13 Relative Brightness Regression Results

Square	0.648557
RSquare Adj	0.647773
Root Mean Square Error	0.8859
Mean of Response	1.688889
Observations (or Sum Wgts)	450

Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	-0.003752	0.158724	-0.02	0.9812
P_J	4.1486291	0.317296	13.07	<.0001

Microsoft Excel® reports the following 95% confidence intervals on the mean and slope:

Intercept	(-.1456, .138095)
P_J Slope	(3.865, 4.432)

A graph displaying the widest range encompassed by the 95% confidence intervals of the estimates is shown in Figure 4.3.

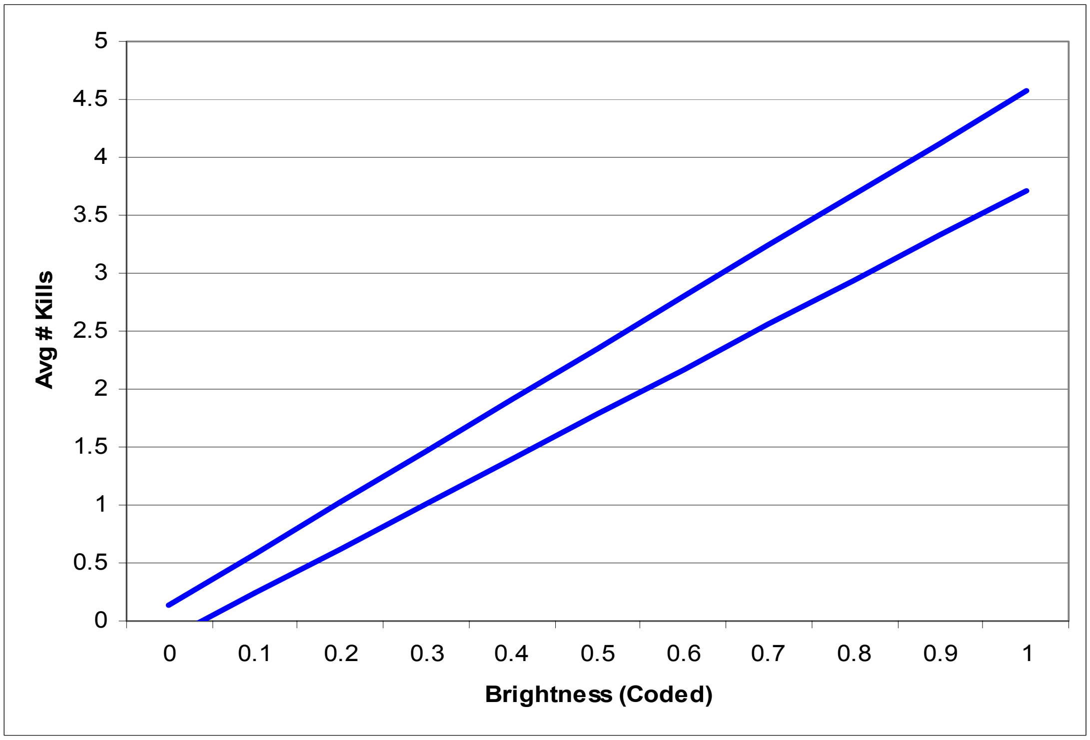

Figure 4. 3 Average Kills vs. Brightness (Coded)

Summary

This chapter summarizes the numerical results of the statistical analyses performed on the simulation output. A discussion of the results continues in Chapter 5 with details about aggregating the numerical results into THUNDER. Chapter 5 also provides conclusions about both EADSIM and THUNDER based on the results of this effort.

5. Conclusions

Overview

This final chapter offers important conclusions from the research documented in the previous four chapters. Though numerical results are presented in Chapter 4, they are revisited to address their significance in aggregation into THUNDER. Additionally, this chapter provides a final assessment about the strengths and weaknesses of the modeling approach used to incorporate the scenario of interest into EADSIM. Beginning with a discussion of how this effort changed from the original research plan may not only help the reader understand the results presented, but document obstacles overcome to complete the research.

Deviations from research plan

The research plan first proposed the use of response surface techniques. Such an approach hoped to answer questions about which dimensions or factors of the HEL modeling problem are most significant as presented in EADSIM. This approach was abandoned after determining that EADSIM laser engagements are primarily deterministic after detection for the exception of a single random number draw from a uniform distribution with a minimum value of 0 and a maximum value of 100.

Secondly, as documented in Chapter 4, the experimental design was expanded from the initial proposal. The factors originally proposed were Targeting Priority and Jitter. However, Altitude, Azimuth, and Power were later added. The added factors were not included to complete a factorial experiment, but allow more analysis and subsequent inferences about the results.

Thirdly, the target airfield was moved farther south in the EADSIM scenarios. The default cruise missile entity in EADSIM flies a search pattern in an attempt to attack the target after completing the user defined flight path. From a low flying flight path, the cruise missile entity flies in a climbing circle pattern to attain the proper altitude and speed to carry out an attack. To prevent the circling pattern from being flown within the engagement volume of the ATL, the position of the target airfield was moved.

Inputs for EADSIM

For ATL engagements in EADSIM, user inputs are required for data elements, as well as various lookup tables. EADSIM data elements must be created or modified to model, at a minimum, an ATL airframe, weapon, sensor, and ruleset. The parameters for each data element are explained in the EADSIM v9.00 Methodology Manual. Two critical pieces of information which must be included in lookup tables are laser propagation and target vulnerability tables. These tables are constructed by the user outside of the constructs of EADSIM, and then transferred into EADSIM.

In this research, the propagation table is constructed by calculating peak intensity from brightness divided by the square of the ranged distance. This is considered a first order model and varies with changes in the description of the laser parameters and ranged distance. Any change in laser parameters requires a different propagation table, unless a clever method is applied for equivalent circumstances, as is done with power and described in Chapter 4. The reader should also note more complex propagation tables may be built with more detailed models of propagation and indexing the table by one or more additional dimension described in the EADSIM v9.00 Reference Manual.

Another critical input for this scenario is the vulnerability lookup table. Though this research used the energy of vaporization of three centimeters of aluminum, more complex models are possible. An easy improvement would be the adjustment of vulnerability for each aimpoint, rather than assuming the nose, wing, and fuselage are equally vulnerable. Additionally, greater dimensionality is possible in the table, rather than indexing by intensity and survivability percentile (P_k) alone. Yet another way to improve the vulnerability table is include the contributions of varying spot size, which would also require a correspondingly detailed propagation table.

As mentioned, the propagation and vulnerability tables are created by the user. Since they are created outside of EADSIM, there are few limits on their construction except they be indexed by appropriate parameters identified in the EADSIM v9.00 Reference Manual. Users may develop the tables using independent models, but may also use results of more detailed models such as those at the engineering level of the model hierarchy.

Outputs from EADSIM

From the reports generated by EADSIM, two types of data are readily available, lasing start time and lasing end time. From this data, the two MOEs are calculated, fraction of kills and total lasing time. Other MOEs are possible but must be calculated from the limited data output available from a laser engagement in EADSIM. Chapter 4 details the analysis of the MOE fraction of kills, but doesn't address total lasing time.

Total lasing time is the sum of the lasing time for each ATL-target engagement. The individual lasing times are highly correlated. Given a lasing time and the order in

which the target is destroyed, a prediction may be made about the length of subsequent times to kill. For example, the second time to kill is most likely shorter than the first time to kill. The correlation may be attributed to the fact that in the scenario, the ATL engages the cruise missiles as they approach its orbit. The ATL continues to engage as the cruise missiles close in, thus reducing the range between laser source and target, and decreasing the required dwell time. Such a strong correlation renders the MOE total lasing time undesirable for analysis purposes.

Besides using the output from EADSIM for analysis, analysts may wish to feed campaign level models. However, aggregation is difficult because of the characteristics of EADSIM and the uniqueness of laser weapons.

Aggregation into THUNDER

The deterministic nature of EADSIM makes aggregation into THUNDER very difficult. Though EADSIM randomly assigns a survivability percentile to a laser weapon's target, the impact of the draw is realized only after referencing the target's vulnerability table, which is created by the user. Hence, variation in kill times may only be artificially induced by the modeler during vulnerability table creation.

EADSIM users may eliminate the stochastic portion of a laser engagement altogether by using a single value for a probability of kill. Such an approach to laser weapon lethality would fit easily into the input tables for THUNDER in the form of a single shot probability to kill. Doing so, however, ignores the unique nature of lasers.

Though conventional weapons such as bombs, missiles, and bullets are employed in discrete packages (e.g. five rounds of ammunition, 2 missile salvo, etc.), the same is

not true for laser weapons. A laser may engage a target for a continuous time interval until the laser fails to irradiate or the decision is made to disengage. A single shot probability of kill is meaningless in the context of a laser weapon. Even an attempt to discretize a kill probability by using a measure like a time interval probability of kill is insufficient because of strong dependencies on range and a correlation with the amount of energy placed on target in preceding time intervals.

Even if a suitable probability of kill measure could be created, it would certainly change with atmospheric conditions. The documentation for the THUNDER model explains the effects of weather on weapon effectiveness in the use of an input file called airgrdpk.dat, which describes air-to-ground versus target effectiveness. (THUNDER Methodology, 184) To account for changes in laser propagation with variations in atmosphere, airgrdpk.dat would need to be modified or a similar file created. The detail in such a file would likely need to be immense to model the sensitivities of a laser weapon to changes in atmosphere. The modification or creation of a weather dependent table in THUNDER to describe laser effectiveness could be accomplished using cross resolution modeling techniques. Using the results of EADSIM runs to populate a table would retain the resolution of the mission level model in the campaign level model.

Limitations of Modeling Laser Weapons

Though the combat models examined have the capability to model the lethal aspect of a laser weapon engaging a target, some key features of a laser weapon are not modeled. The omission of these features hinders the accurate representation of laser weapons to decision-makers not familiar with their benefits. EADSIM does not account

for a soft kill such as destroying or disrupting sensors on a target. Though the target would not be destroyed, the target's mission would not be accomplished. Another feature of laser weapons not modeled is the reduction of collateral damage. While strike weapons such as bombs and missiles have characteristic lethal radii, a laser weapon uses a spot size on the order of centimeters to apply lethal energy. Finally, non-lethal effects are not modeled. A laser weapon's damage capability may be considered a continuum. When a desired effect is attained, a laser may be disengaged. For example, the ATL will have the capability to destroy a vehicle's tires, disabling the vehicle but not killing or injuring its occupants.

Final notes on EADSIM

There are many additional points of interest in EADSIM which are not covered in the rest of this document. These points are notable because they may impact an analyst's interpretation of EADSIM results or serve as de facto assumptions in the simulation itself. The points discussed in this section are not presented in any order of significance.

EADSIM doesn't capture the stochastic nature of the atmosphere. The randomness of atmospheric conditions is recognized in the scientific community, but it is not addressed in EADSIM's intensity based lethality model. In the propagation model used in this effort, using a random number draw for transmission and wavefront error are two ways to attempt to capture a stochastic atmosphere.

EADSIM, like many models, has a very strong dependence on data. The intensity based lethality model is very flexible. There are many dimensions of propagation and vulnerability not even included in this effort. However, the price of flexibility is paid by

the user. The user must provide the appropriate data for the propagation and vulnerability conditions desired.

Laser weapons in version 9.00b are unable to handle a target which is detected but is obscured behind terrain during the lase phase of an engagement. The original terrain map used in this research, which included hills, was changed because several simulation runs terminated when a hill blocked a cruise missile target as the ATL engaged it.

This research did not explore the full capability of EADSIM. Mission models are normally used for a broader engagement of longer durations using mixed forces. The scenario used in this effort doesn't credit EADSIM for its capabilities to model mixed forces and their interactions.

EADSIM doesn't have the agility to adjust for dynamically changing atmospheric conditions. A new propagation table is required for different atmospheric conditions, and there is no known way to change the propagation table while a scenario is running. For greater fidelity, EADSIM could be modified to read from one of many propagation tables based on the interaction of the battlefield with the atmosphere. For instance, a vehicle moving at a specified velocity over certain terrain may alter the atmosphere by generating a plume of smoke, altering the index of refraction in air immediately adjacent to it due to heat radiating from its engine, and contributing particulate matter in the form of dust thrown from wheels or treads. EADSIM may be modified to select an appropriate propagation table based on predetermined estimates of a vehicle's interaction with the atmosphere. However, a change to EADSIM of such magnitude may still not be adequate.

The atmospheric conditions resulting from a vehicle's movement would change with time, and the effect on a laser beam could differ with relative target position. Winds would presumably diffuse smoke and dust, so their effect on the atmosphere would be time dependent. If a laser weapon attacked a target head-on, the plume of smoke and dust would be less influential than an attack from behind. EADSIM does not currently have the ability to assess atmospheric conditions with time, nor does it have the ability to stipulate propagation characteristics based on the relative angle between attacker and target velocity vectors.

Appendix A. Arena Models

Cruise Missile Location Generation

Cruise missiles are assumed to launch from a rectangular area of probability on the terrain map. The launch locations of the cruise missiles are generated by the Arena® model shown in Figure A.1. The "Assign Lat" node assigns a number from the Uniform (29.8, 29.97) distribution using random number stream 1. The "Assign Long" node assigns a number from the Uniform (47.35, 47.75) distribution using random number stream 2.

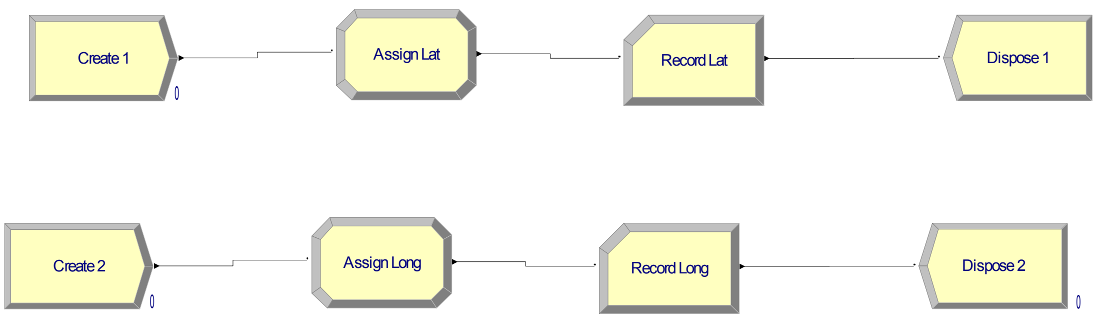

Figure A. 1 Launch Position Generation

ATL Orbit Position

To simulate the ATL being in a different position along its circular orbit when the cruise missiles are launched, a random number draw is made from the Uniform (0, 420) distribution using stream 3. The upper limit of the distribution used was determined by the time it takes for the ATL to complete one orbit. The Arena® model used for recording the draws is shown in Figure A.2.

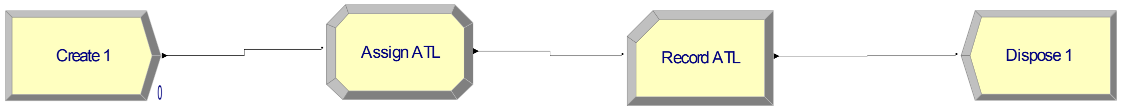

Figure A. 2 ATL Position Generation

Appendix B. Propagation Table

The propagation table was generated using the following Visual Basic code. The case for no jitter is shown.

```
Option Explicit
Sub Brightness()
'   This program populates a table of laser intensity
' incident on a target indexed by range, altitude, and azimuth
'
' Rad=Radiant flux density in W/cm2
' B=Brightness in Watts/Steradian
' D=Diameter of transmitting aperture in meters
' P=Power of laser in Watts
' LAM=Wavelength in micrometers
' WE=Wavefront error in rms as a % of wavelength
' JIT=Jitter in rms as a % of wavelength/diameter
' t=Transmission of atmosphere in %
' RNG=Horizontal range to target in meters
' SPOT = Spot size in cm
' E0 = Flux density (J/cm2)
' Pi=Pi
' row=Row output counter

Dim B, L, Pi, RAD, E0 As Double
Dim LAM, WE, JIT, P, t, RNG, SPOT As Double
Dim D As Single
Dim row As Integer

' Clear worksheet
Worksheets("Sheet1").Range("A1:AZ1000").ClearContents


' Specification of parameter values
D = 1
P = 50000
LAM = 1.315 * 10 ^ (-6)
WE = 0.2 * LAM
JIT = 0
t = 0.9
Pi = Application.WorksheetFunction.Pi()
E0 = 113200 * 2 ' TO ACCOUNT FOR REFLECTIVITY

' Calculation of brightness
```

```
B = ((Pi * D ^ 2 * P) / (4 * LAM ^ 2)) * Exp(-((2 * Pi * WE) / LAM) ^ 2) _
    * (1 / (1 + Pi ^ 2 / 2 * (JIT / (LAM / D)) ^ 2)) * t

' Initialize variable RNG and row counter
RNG = 500
row = 1

' Initialize column headings
With Range("A1")
    .Value = "Range (m)"
    .Font.Bold = True
    .Offset(0, 1).Value = "RAD (W/cm2)"
    .Offset(0, 1).Font.Bold = True
    .Offset(0, 2).Value = "SPOT (cm)"
    .Offset(0, 2).Font.Bold = True
    .Offset(0, 3).Value = "DWELL (s)"
    .Offset(0, 3).Font.Bold = True
End With

' Loop pathlength dimensions
Do While RNG < 15500
    ' Calculate RAD and convert to W/cm2
    RAD = B / (RNG ^ 2 * 100 ^ 2)
    ' SPOT = 1.22 * LAM * RNG / (D * 100)
    Range("A1").Offset(row, 0).Value = RNG
    Range("A1").Offset(row, 1).Value = RAD
    ' Range("A1").Offset(row, 2).Value = SPOT
    Range("A1").Offset(row, 3).Value = E0 / RAD
    row = row + 1
    RNG = RNG + 200
Loop
End Sub
```

The output for the case of zero jitter appears in the following table. The first column is the range in meters. The second column displays the radiance at range in W/Cm2. The third column shows the required dwell time for a kill and is used in the vulnerability table generation.

Range (m)	RAD (W/cm2)	DWELL (s)
500	1685390.432	0.134330892
700	859893.0774	0.263288548
900	520182.232	0.43523209
1100	348221.1636	0.650161517
1300	249318.1112	0.90807683
1500	187265.6035	1.208978028
1700	145795.02	1.552865111
1900	116716.7889	1.93973808
2100	95543.67527	2.369596934
2300	79649.83137	2.842441674
2500	67415.61727	3.358272299
2700	57798.02578	3.91708881
2900	50100.78572	4.518891206
3100	43844.70426	5.163679487
3300	38691.2404	5.851453654
3500	34395.7231	6.582213706
3700	30777.76537	7.355959644
3900	27702.01236	8.172691467
4100	25065.29494	9.032409176
4300	22787.86414	9.93511277
4500	20807.28928	10.88080225
4700	19074.13345	11.86947761
4900	17548.83831	12.90113886
5100	16199.44667	13.975786
5300	14999.91484	15.09341902
5500	13928.84654	16.25403793
5700	12968.5321	17.45764272
5900	12104.21166	18.7042334
6100	11323.50465	19.99380996
6300	10615.96392	21.32637241
6500	9972.724448	22.70192074
6700	9386.22428	24.12045496
6900	8849.981263	25.58197507
7100	8358.413171	27.08648106
7300	7906.691836	28.63397293
7500	7490.624141	30.22445069
7700	7106.554359	31.85791434
7900	6751.283575	33.53436387
8100	6422.002864	35.25379929
8300	6116.237595	37.01622059
8500	5831.800802	38.82162778
8700	5566.753969	40.67002085
8900	5319.373917	42.56139981
9100	5088.124718	44.49576465
9300	4871.633807	46.47311538

9500	4668.671556	48.493452
9700	4478.133786	50.5567745
9900	4299.026711	52.66308288
10100	4130.453955	54.81237716
10300	3971.605316	57.00465731
10500	3821.747011	59.23992336
10700	3680.213188	61.51817528
10900	3546.398518	63.8394131
11100	3419.751708	66.20363679
11300	3299.769817	68.61084638
11500	3185.993255	71.06104185
11700	3078.001373	73.5542232
11900	2975.408572	76.09039044
12100	2877.860856	78.66954357
12300	2785.032771	81.29168258
12500	2696.624691	83.95680748
12700	2612.360394	86.66491826
12900	2531.984904	89.41601493
13100	2455.26256	92.21009748
13300	2381.975284	95.04716592
13500	2311.921031	97.92722024
13700	2244.912398	100.8502604
13900	2180.775363	103.8162865
14100	2119.348161	106.8252985
14300	2060.480258	109.8772964
14500	2004.031429	112.9722801
14700	1949.870924	116.1102498
14900	1897.876708	119.2912053
15100	1847.934774	122.5151467
15300	1799.938519	125.782074

The following table shows the values for radiance and required dwell time for the case of jitter inducing a spot size five times larger than the case of no jitter.

Range (m)	**RAD (W/cm2)**	**DWELL (s)**
500	67415.61727	3.358272299
700	34395.7231	6.582213706
900	20807.28928	10.88080225
1100	13928.84654	16.25403793
1300	9972.724448	22.70192074
1500	7490.624141	30.22445069
1700	5831.800802	38.82162778
1900	4668.671556	48.493452
2100	3821.747011	59.23992336

2300	3185.993255	71.06104185
2500	2696.624691	83.95680748
2700	2311.921031	97.92722024
2900	2004.031429	112.9722801
3100	1753.78817	129.0919872
3300	1547.649616	146.2863413
3500	1375.828924	164.5553427
3700	1231.110615	183.8989911
3900	1108.080494	204.3172867
4100	1002.611798	225.8102294
4300	911.5145656	248.3778192
4500	832.2915712	272.0200562
4700	762.965338	296.7369403
4900	701.9535326	322.5284716
5100	647.9778669	349.39465
5300	599.9965937	377.3354755
5500	557.1538617	406.3509482
5700	518.741284	436.441068
5900	484.1684665	467.6058349
6100	452.9401859	499.845249
6300	424.6385567	533.1593102
6500	398.9089779	567.5480185
6700	375.4489712	603.011374
6900	353.9992505	639.5493766
7100	334.3365268	677.1620264
7300	316.2676734	715.8493233
7500	299.6249656	755.6112673
7700	284.2621744	796.4478584
7900	270.051343	838.3590967
8100	256.8801146	881.3449822
8300	244.6495038	925.4055147
8500	233.2720321	970.5406944
8700	222.6701588	1016.750521
8900	212.7749567	1064.034995
9100	203.5249887	1112.394116
9300	194.8653523	1161.827885
9500	186.7468622	1212.3363
9700	179.1253514	1263.919362
9900	171.9610684	1316.577072
10100	165.2181582	1370.309429
10300	158.8642126	1425.116433
10500	152.8698804	1480.998084
10700	147.2085275	1537.954382
10900	141.8559407	1595.985327
11100	136.7900683	1655.09092
11300	131.9907927	1715.271159
11500	127.4397302	1776.526046

11700	123.1200549	1838.85558
11900	119.0163429	1902.259761
12100	115.1144342	1966.738589
12300	111.4013108	2032.292065
12500	107.8649876	2098.920187
12700	104.4944158	2166.622956
12900	101.2793962	2235.400373
13100	98.2105024	2305.252437
13300	95.27901135	2376.179148
13500	92.47684125	2448.180506
13700	89.79649591	2521.256511
13900	87.23101453	2595.407164
14100	84.77392645	2670.632463
14300	82.41921032	2746.93241
14500	80.16125716	2824.307004
14700	77.99483695	2902.756244
14900	75.91506832	2982.280132
15100	73.91739098	3062.878668
15300	71.99754076	3144.55185

Appendix C. Vulnerability Table Generation

The following table documents the values for dwell time in seconds used in the cruise missile vulnerability table. The increase in dwell time with survivability percentile is explained in Chapter 3. The column labeled RAD is used as the incident intensity in EADSIM. Subsequent columns indicate the level of survivability drawn for the cruise missile in EADSIM.

RAD (W/cm2)	0-70	70-80	80-90	90-100	100
1685390.432	0.134331	0.147764	0.161197	0.17463	190
859893.0774	0.263289	0.289617	0.315946	0.342275	190
520182.232	0.435232	0.478755	0.522279	0.565802	190
348221.1636	0.650162	0.715178	0.780194	0.84521	190
249318.1112	0.908077	0.998885	1.089692	1.1805	190
187265.6035	1.208978	1.329876	1.450774	1.571671	190
145795.02	1.552865	1.708152	1.863438	2.018725	190
116716.7889	1.939738	2.133712	2.327686	2.52166	190
95543.67527	2.369597	2.606557	2.843516	3.080476	190
79649.83137	2.842442	3.126686	3.41093	3.695174	190
67415.61727	3.358272	3.6941	4.029927	4.365754	190
57798.02578	3.917089	4.308798	4.700507	5.092215	190
50100.78572	4.518891	4.97078	5.422669	5.874559	190
43844.70426	5.163679	5.680047	6.196415	6.712783	190
38691.2404	5.851454	6.436599	7.021744	7.60689	190
34395.7231	6.582214	7.240435	7.898656	8.556878	190
30777.76537	7.35596	8.091556	8.827152	9.562748	190
27702.01236	8.172691	8.989961	9.80723	10.6245	190
25065.29494	9.032409	9.93565	10.83889	11.74213	190
22787.86414	9.935113	10.92862	11.92214	12.91565	190
20807.28928	10.8808	11.96888	13.05696	14.14504	190
19074.13345	11.86948	13.05643	14.24337	15.43032	190
17548.83831	12.90114	14.19125	15.48137	16.77148	190
16199.44667	13.97579	15.37336	16.77094	18.16852	190
14999.91484	15.09342	16.60276	18.1121	19.62144	190
13928.84654	16.25404	17.87944	19.50485	21.13025	190
12968.5321	17.45764	19.20341	20.94917	22.69494	190
12104.21166	18.70423	20.57466	22.44508	24.3155	190
11323.50465	19.99381	21.99319	23.99257	25.99195	190
10615.96392	21.32637	23.45901	25.59165	27.72428	190
9972.724448	22.70192	24.97211	27.2423	29.5125	190

9386.22428	24.12045	26.5325	28.94455	31.35659	190
8849.981263	25.58198	28.14017	30.69837	33.25657	190
8358.413171	27.08648	29.79513	32.50378	35.21243	190
7906.691836	28.63397	31.49737	34.36077	37.22416	190
7490.624141	30.22445	33.2469	36.26934	39.29179	190
7106.554359	31.85791	35.04371	38.2295	41.41529	190
6751.283575	33.53436	36.8878	40.24124	43.59467	190
6422.002864	35.2538	38.77918	42.30456	45.82994	190
6116.237595	37.01622	40.71784	44.41946	48.12109	190
5831.800802	38.82163	42.70379	46.58595	50.46812	190
5566.753969	40.67002	44.73702	48.80403	52.87103	190
5319.373917	42.5614	46.81754	51.07368	55.32982	190
5088.124718	44.49576	48.94534	53.39492	57.84449	190
4871.633807	46.47312	51.12043	55.76774	60.41505	190
4668.671556	48.49345	53.3428	58.19214	63.04149	190
4478.133786	50.55677	55.61245	60.66813	65.72381	190
4299.026711	52.66308	57.92939	63.1957	68.46201	190
4130.453955	54.81238	60.29361	65.77485	71.25609	190
3971.605316	57.00466	62.70512	68.40559	74.10605	190
3821.747011	59.23992	65.16392	71.08791	77.0119	190
3680.213188	61.51818	67.66999	73.82181	79.97363	190
3546.398518	63.83941	70.22335	76.6073	82.99124	190
3419.751708	66.20364	72.824	79.44436	86.06473	190
3299.769817	68.61085	75.47193	82.33302	89.1941	190
3185.993255	71.06104	78.16715	85.27325	92.37935	190
3078.001373	73.55422	80.90965	88.26507	95.62049	190
2975.408572	76.09039	83.69943	91.30847	98.91751	190
2877.860856	78.66954	86.5365	94.40345	102.2704	190
2785.032771	81.29168	89.42085	97.55002	105.6792	190
2696.624691	83.95681	92.35249	100.7482	109.1438	190
2612.360394	86.66492	95.33141	103.9979	112.6644	190
2531.984904	89.41601	98.35762	107.2992	116.2408	190
2455.26256	92.2101	101.4311	110.6521	119.8731	190
2381.975284	95.04717	104.5519	114.0566	123.5613	190
2311.921031	97.92722	107.7199	117.5127	127.3054	190
2244.912398	100.8503	110.9353	121.0203	131.1053	190
2180.775363	103.8163	114.1979	124.5795	134.9612	190
2119.348161	106.8253	117.5078	128.1904	138.8729	190
2060.480258	109.8773	120.865	131.8528	142.8405	190
2004.031429	112.9723	124.2695	135.5667	146.864	190
1949.870924	116.1102	127.7213	139.3323	150.9433	190
1897.876708	119.2912	131.2203	143.1494	155.0786	190
1847.934774	122.5151	134.7667	147.0182	159.2697	190
1799.938519	125.7821	138.3603	150.9385	163.5167	190
1753.78817	129.092	142.0012	154.9104	167.8196	190
1547.649616	146.2863	160.915	175.5436	190.1722	190
1375.828924	164.5553	181.0109	197.4664	213.9219	190

1231.110615	183.899	202.2889	220.6788	239.0687	190

Appendix D. EADSIM Data Elements

Overview

This appendix provides details about the EADSIM data elements modified and created to model the scenario described in Chapter 3. It is arranged by system from the most basic element to the complete system. Only the parameters which were changed for element modification and all new element parameters are documented. All other parameters are left at the default settings from the database provided with EADSIM version 9.00b.

Advanced Tactical Laser (ATL) System

The ATL system was created by combining modified data elements existing in the default database provided with EADSIM version 9.00b. It is the combination of an airframe, weapon, sensor, and ruleset.

ATL Airframe.

The ATL airframe element used is based on the "BlueFighter" airframe element.

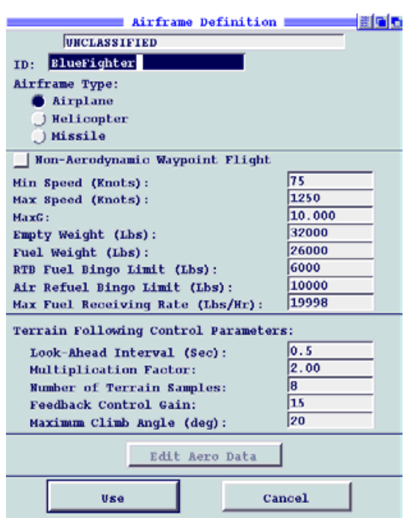

Figure D. 1 Airframe Definition Window

ATL Weapon.

The laser weapon used on the ATL system is based on the “S_Laser” weapon element.

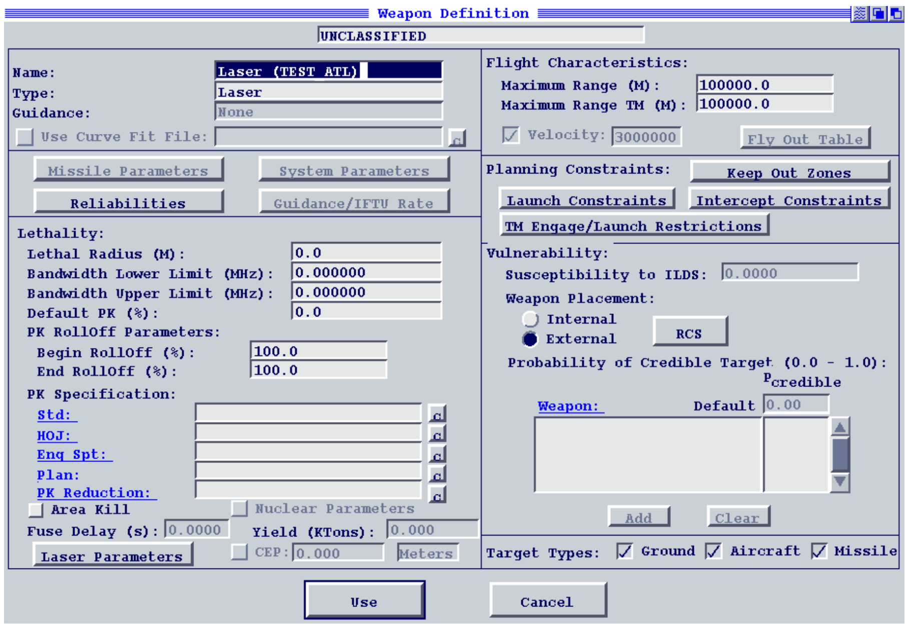

Figure D. 2 Weapon Definition Window

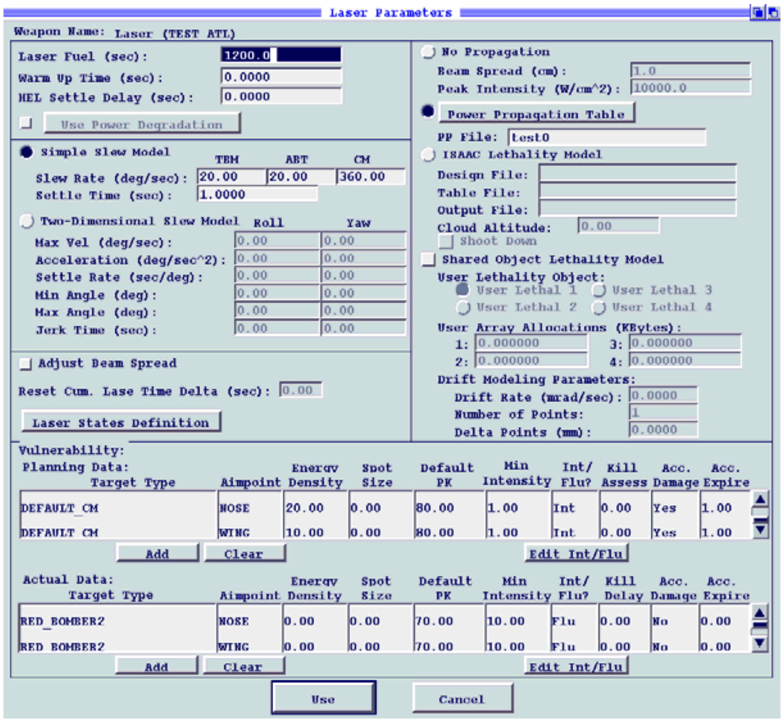

Figure D. 3 Laser Parameters Window

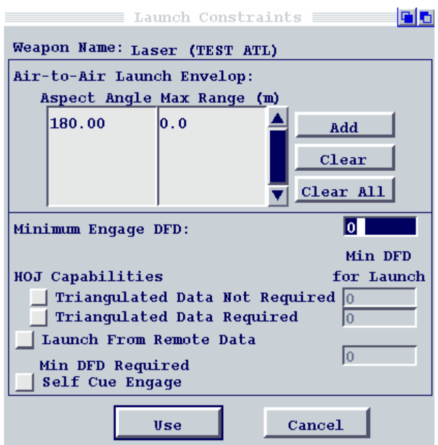

Figure D. 4 Launch Constraints Window

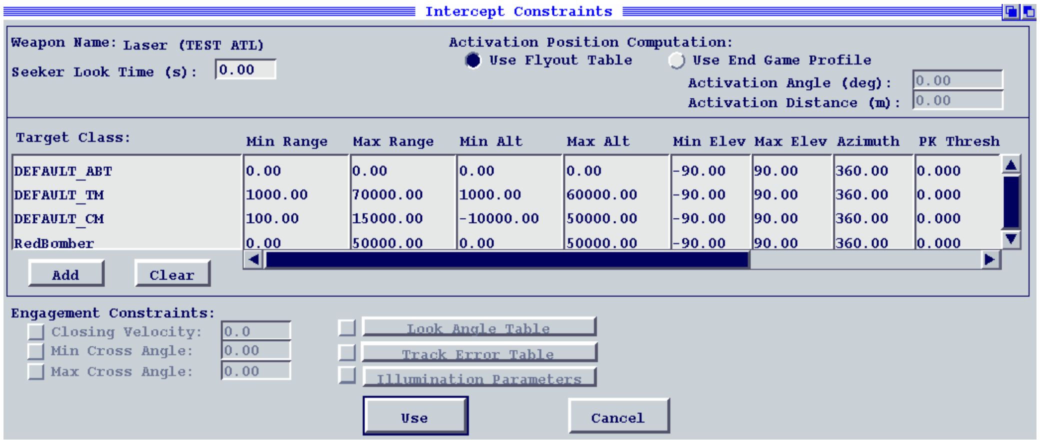

Figure D. 5 Intercept Constraints Window

ATL Sensor.

The sensor used on the ATL system is based on the AB_Radar(Acft) sensor element.

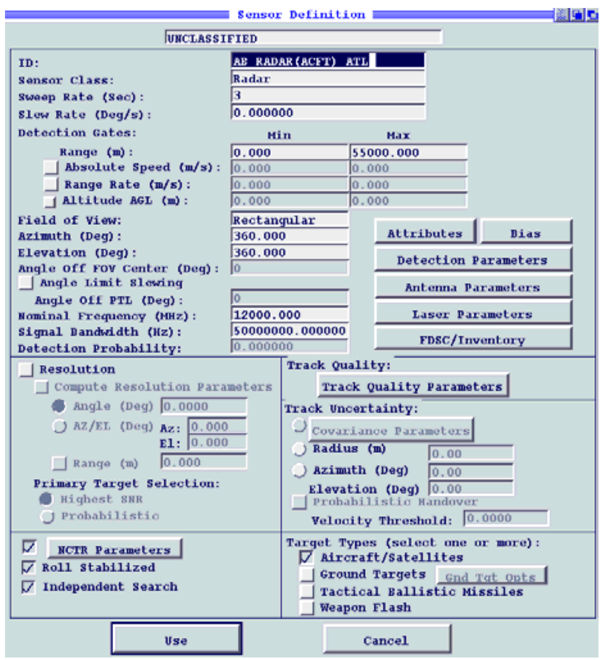

Figure D. 6 Sensor Definition Window

ATL Ruleset.

The ruleset used on the ATL system is based on the Laser ruleset element. Only the "Target Select" parameters were changed and are shown in the following figure.

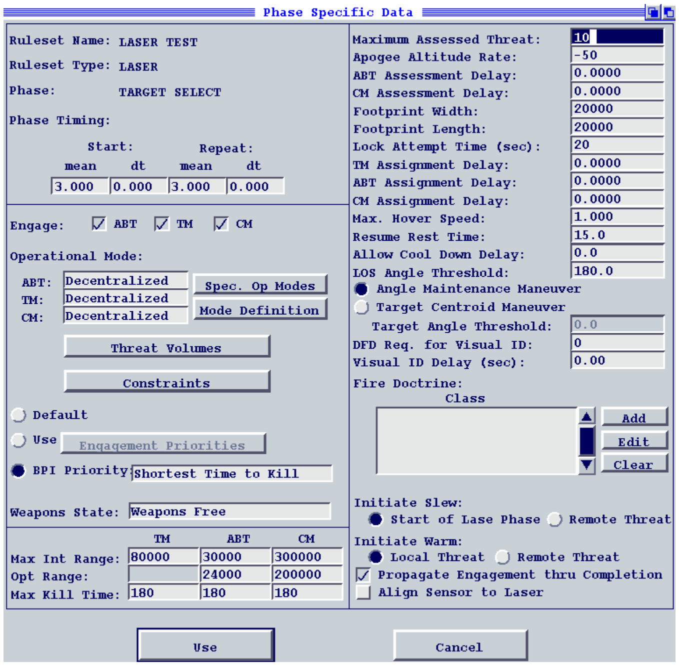

Figure D. 7 Target Select Phase Window

Cruise Missile System

The cruise missile system element is unchanged from the default element.

System Deployment

Once the systems are constructed, they are deployed. The deployment of the ATL and an example of the cruise missile are shown.

ATL Deployment.

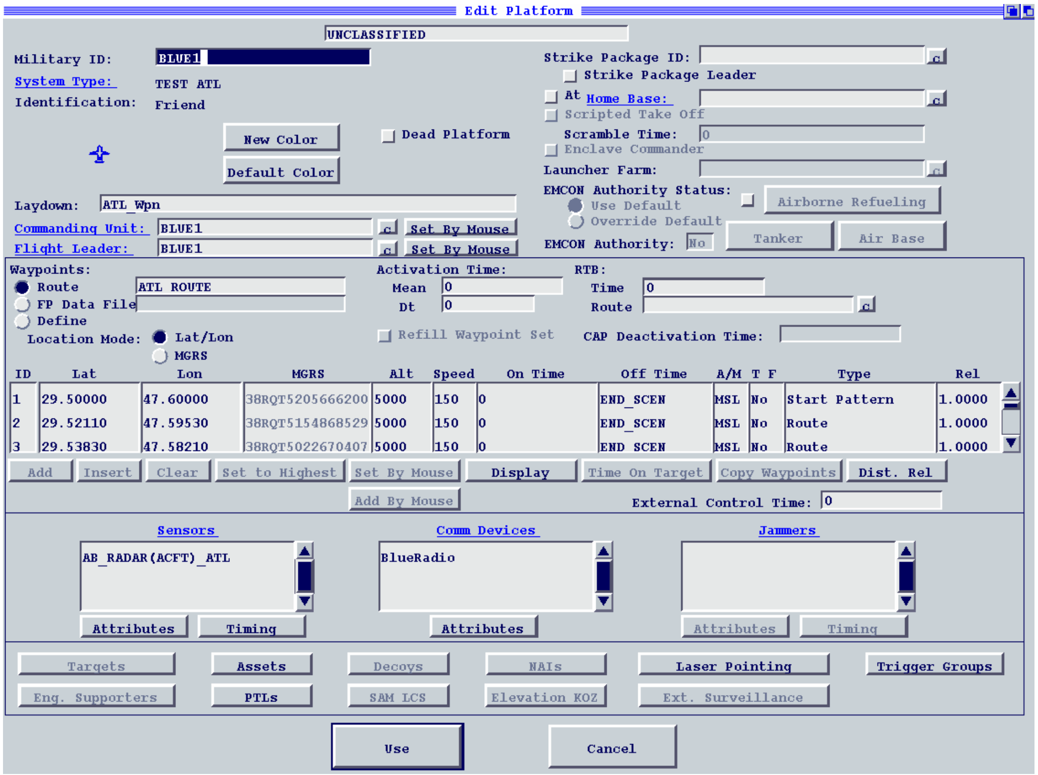

Figure D. 8 ATL Deployment Window

Cruise Missile Deployment

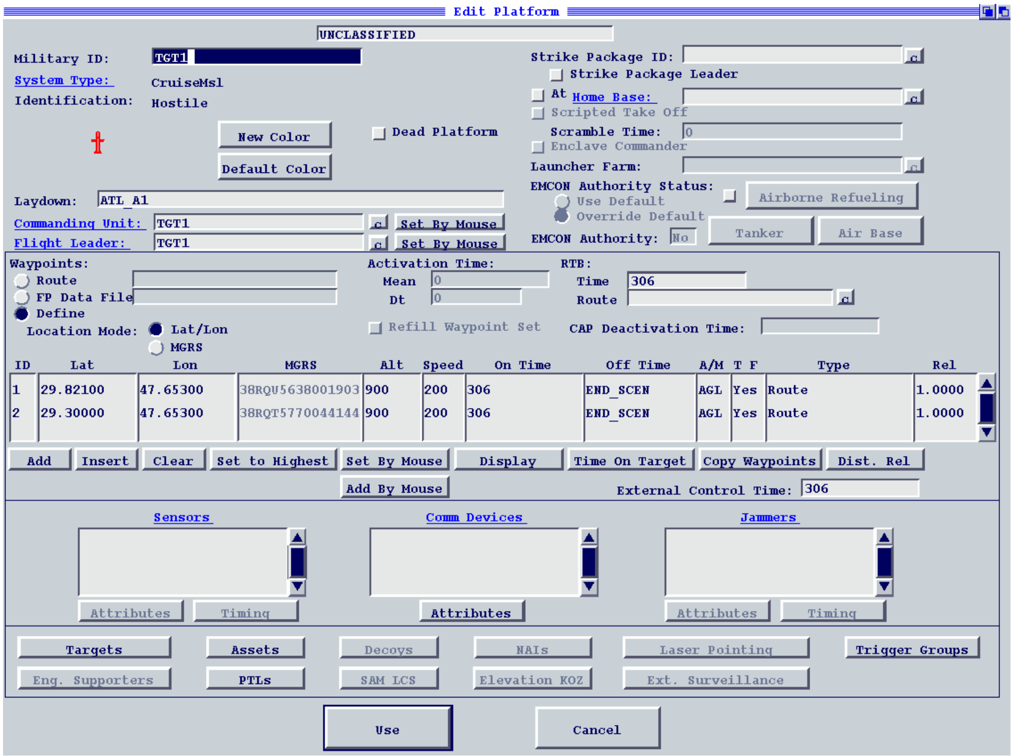

Figure D. 9 Cruise Missile Deployment Window

Appendix E. Simulation Output Results

Overview

This appendix documents the results of the simulation runs accomplished in EADSIM. The result of each replication at all tested design points appears in the following table.

Legend

The column headings are shortened for inclusion in a single page width. This section provides a legend for each column heading and the values possible.

S	= Scenario (1 to 9)
Pri	= Priority (Shortest time to kill, longest, track maturity)
R	= Replication (1 to 5)
Alt	= ATL Altitude (High = 5000 ft, Low = 2000 ft)
Jit	= Jitter (0 jitter, 5x spot size)
Az	= Weapon coverage or azimuth around ATL (180˚, 270˚, 360˚)
Pow	= Power (Low = 50000W, High = 100000W)
K	= Number of kills accumulated in simulation run
TK_i	= Time to kill i^{th} target in seconds
Eng	= Number of targets engaged

S	Pri	R	Alt	Jit	Az	Pow	K	TK1	TK2	TK3	TK4	TK5	TK6	Eng
1	Mat	1	High	0	180	Low	0							0
1	Mat	2	High	0	180	Low	0							0
1	Mat	3	High	0	180	Low	0							0
1	Mat	4	High	0	180	Low	0							0
1	Mat	5	High	0	180	Low	0							0
2	Mat	1	High	0	180	Low	1	23.31						1
2	Mat	2	High	0	180	Low	1	23.31						1
2	Mat	3	High	0	180	Low	1	24.25						1
2	Mat	4	High	0	180	Low	1	24						1
2	Mat	5	High	0	180	Low	1	23.93						1
3	Long	1	High	0	180	Low	1	37.19						1
3	Long	2	High	0	180	Low	1	38.73						1
3	Long	3	High	0	180	Low	1	36.58						1
3	Long	4	High	0	180	Low	1	36.46						1
3	Long	5	High	0	180	Low	1	40.81						1

S	Pri	R	Alt	Jit	Az	Pow	K	TK1	TK2	TK3	TK4	TK5	TK6	Eng
4	Long	1	High	0	180	Low	1	28.01						1
4	Long	2	High	0	180	Low	1	28.28						1
4	Long	3	High	0	180	Low	1	28.76						1
4	Long	4	High	0	180	Low	1	28.31						1
4	Long	5	High	0	180	Low	1	32.62						1
5	Short	1	High	0	180	Low	2	61.83	56.31					2
5	Short	2	High	0	180	Low	2	66.45	60.52					2
5	Short	3	High	0	180	Low	1	53.01						2
5	Short	4	High	0	180	Low	2	53.11	55.52					2
5	Short	5	High	0	180	Low	2	61.66	56.33					2
6	Short	1	High	0	180	Low	0							0
6	Short	2	High	0	180	Low	0							0
6	Short	3	High	0	180	Low	0							0
6	Short	4	High	0	180	Low	0							0
6	Short	5	High	0	180	Low	0							0
7	Short	1	High	0	180	Low	2	18.7	25.62					2
7	Short	2	High	0	180	Low	2	18.96	24.61					2
7	Short	3	High	0	180	Low	2	18.75	22.93					2
7	Short	4	High	0	180	Low	2	18.7	23.63					2
7	Short	5	High	0	180	Low	2	18.7	23.63					2
8	Mat	1	High	0	180	Low	0							0
8	Mat	2	High	0	180	Low	0							0
8	Mat	3	High	0	180	Low	0							0
8	Mat	4	High	0	180	Low	0							0
8	Mat	5	High	0	180	Low	0							0
9	Long	1	High	0	180	Low	0							0
9	Long	2	High	0	180	Low	0							0
9	Long	3	High	0	180	Low	0							0
9	Long	4	High	0	180	Low	0							0
9	Long	5	High	0	180	Low	0							0
1	Mat	1	Low	0	180	Low	0							0
1	Mat	2	Low	0	180	Low	0							0
1	Mat	3	Low	0	180	Low	0							0
1	Mat	4	Low	0	180	Low	0							0
1	Mat	5	Low	0	180	Low	0							0
2	Mat	1	Low	0	180	Low	2	25.48	9					2
2	Mat	2	Low	0	180	Low	2	26.38	10.3					2
2	Mat	3	Low	0	180	Low	2	28.68	7.88					2
2	Mat	4	Low	0	180	Low	2	24.84	10.84					2
2	Mat	5	Low	0	180	Low	2	25.18	11.15					2
3	Long	1	Low	0	180	Low	1	33.41						1
3	Long	2	Low	0	180	Low	1	33.25						1
3	Long	3	Low	0	180	Low	1	36						1
3	Long	4	Low	0	180	Low	1	33.13						1
3	Long	5	Low	0	180	Low	1	33.57						1
4	Long	1	Low	0	180	Low	3	36.56	20.33	18				3

S	Pri	R	Alt	Jit	Az	Pow	K	TK1	TK2	TK3	TK4	TK5	TK6	Eng
4	Long	2	Low	0	180	Low	3	35.69	22.78	15.87				3
4	Long	3	Low	0	180	Low	3	36.54	20.44	18.18				3
4	Long	4	Low	0	180	Low	3	36	21	19.85				3
4	Long	5	Low	0	180	Low	3	35.69	19.47	18.94				3
5	Short	1	Low	0	180	Low	2	61.83	56.31					2
5	Short	2	Low	0	180	Low	2	46.78	49.02					2
5	Short	3	Low	0	180	Low	2	46.42	53.04					2
5	Short	4	Low	0	180	Low	2	47.49	64.35					2
5	Short	5	Low	0	180	Low	2	46.72	48.87					2
6	Short	1	Low	0	180	Low	1	26.21						1
6	Short	2	Low	0	180	Low	1	29.4						1
6	Short	3	Low	0	180	Low	1	27.71						1
6	Short	4	Low	0	180	Low	1	26.27						1
6	Short	5	Low	0	180	Low	1	26.43						1
7	Short	1	Low	0	180	Low	2	10.88	16.59					2
7	Short	2	Low	0	180	Low	2	10.88	16.93					2
7	Short	3	Low	0	180	Low	2	11.97	17.06					2
7	Short	4	Low	0	180	Low	2	13.06	17.05					2
7	Short	5	Low	0	180	Low	2	10.88	17.61					2
8	Mat	1	Low	0	180	Low	2	30	18.42					2
8	Mat	2	Low	0	180	Low	2	30	22.48					2
8	Mat	3	Low	0	180	Low	2	30	17.87					2
8	Mat	4	Low	0	180	Low	2	30.11	19.35					2
8	Mat	5	Low	0	180	Low	2	30	18					2
9	Long	1	Low	0	180	Low	1	18						1
9	Long	2	Low	0	180	Low	1	17.22						1
9	Long	3	Low	0	180	Low	1	16.78						1
9	Long	4	Low	0	180	Low	1	17.28						1
9	Long	5	Low	0	180	Low	1	18						1
1	Mat	1	High	5x	180	Low	0							0
1	Mat	2	High	5x	180	Low	0							0
1	Mat	3	High	5x	180	Low	0							0
1	Mat	4	High	5x	180	Low	0							0
1	Mat	5	High	5x	180	Low	0							0
2	Mat	1	High	5x	180	Low	0							0
2	Mat	2	High	5x	180	Low	0							0
2	Mat	3	High	5x	180	Low	0							0
2	Mat	4	High	5x	180	Low	0							0
2	Mat	5	High	5x	180	Low	0							0
3	Long	1	High	5x	180	Low	0							0
3	Long	2	High	5x	180	Low	0							0
3	Long	3	High	5x	180	Low	0							0
3	Long	4	High	5x	180	Low	0							0
3	Long	5	High	5x	180	Low	0							0
4	Long	1	High	5x	180	Low	0							0
4	Long	2	High	5x	180	Low	0							0

S	Pri	R	Alt	Jit	Az	Pow	K	TK1	TK2	TK3	TK4	TK5	TK6	Eng
4	Long	3	High	5x	180	Low	0							0
4	Long	4	High	5x	180	Low	0							0
4	Long	5	High	5x	180	Low	0							0
5	Short	1	High	5x	180	Low	0							0
5	Short	2	High	5x	180	Low	0							0
5	Short	3	High	5x	180	Low	0							0
5	Short	4	High	5x	180	Low	0							0
5	Short	5	High	5x	180	Low	0							0
6	Short	1	High	5x	180	Low	0							0
6	Short	2	High	5x	180	Low	0							0
6	Short	3	High	5x	180	Low	0							0
6	Short	4	High	5x	180	Low	0							0
6	Short	5	High	5x	180	Low	0							0
7	Short	1	High	5x	180	Low	0							0
7	Short	2	High	5x	180	Low	0							0
7	Short	3	High	5x	180	Low	0							0
7	Short	4	High	5x	180	Low	0							0
7	Short	5	High	5x	180	Low	0							0
8	Mat	1	High	5x	180	Low	0							0
8	Mat	2	High	5x	180	Low	0							0
8	Mat	3	High	5x	180	Low	0							0
8	Mat	4	High	5x	180	Low	0							0
8	Mat	5	High	5x	180	Low	0							0
9	Long	1	High	5x	180	Low	0							0
9	Long	2	High	5x	180	Low	0							0
9	Long	3	High	5x	180	Low	0							0
9	Long	4	High	5x	180	Low	0							0
9	Long	5	High	5x	180	Low	0							0
1	Mat	1	Low	5x	180	Low	0							0
1	Mat	2	Low	5x	180	Low	0							0
1	Mat	3	Low	5x	180	Low	0							0
1	Mat	4	Low	5x	180	Low	0							0
1	Mat	5	Low	5x	180	Low	0							0
2	Mat	1	Low	5x	180	Low	0							0
2	Mat	2	Low	5x	180	Low	0							0
2	Mat	3	Low	5x	180	Low	0							0
2	Mat	4	Low	5x	180	Low	0							0
2	Mat	5	Low	5x	180	Low	0							0
3	Long	1	Low	5x	180	Low	0							0
3	Long	2	Low	5x	180	Low	0							0
3	Long	3	Low	5x	180	Low	0							0
3	Long	4	Low	5x	180	Low	0							0
3	Long	5	Low	5x	180	Low	0							0
4	Long	1	Low	5x	180	Low	0							0
4	Long	2	Low	5x	180	Low	0							0
4	Long	3	Low	5x	180	Low	0							0

S	Pri	R	Alt	Jit	Az	Pow	K	TK1	TK2	TK3	TK4	TK5	TK6	Eng
4	Long	4	Low	5x	180	Low	0							0
4	Long	5	Low	5x	180	Low	0							0
5	Short	1	Low	5x	180	Low	0							0
5	Short	2	Low	5x	180	Low	0							0
5	Short	3	Low	5x	180	Low	0							0
5	Short	4	Low	5x	180	Low	0							0
5	Short	5	Low	5x	180	Low	0							0
6	Short	1	Low	5x	180	Low	0							0
6	Short	2	Low	5x	180	Low	0							0
6	Short	3	Low	5x	180	Low	0							0
6	Short	4	Low	5x	180	Low	0							0
6	Short	5	Low	5x	180	Low	0							0
7	Short	1	Low	5x	180	Low	0							0
7	Short	2	Low	5x	180	Low	0							0
7	Short	3	Low	5x	180	Low	0							0
7	Short	4	Low	5x	180	Low	0							0
7	Short	5	Low	5x	180	Low	0							0
8	Mat	1	Low	5x	180	Low	0							0
8	Mat	2	Low	5x	180	Low	0							0
8	Mat	3	Low	5x	180	Low	0							0
8	Mat	4	Low	5x	180	Low	0							0
8	Mat	5	Low	5x	180	Low	0							0
9	Long	1	Low	5x	180	Low	0							0
9	Long	2	Low	5x	180	Low	0							0
9	Long	3	Low	5x	180	Low	0							0
9	Long	4	Low	5x	180	Low	0							0
9	Long	5	Low	5x	180	Low	0							0
1	Mat	1	High	0	270	Low	2	43.64	33.1					2
1	Mat	2	High	0	270	Low	2	45.66	32.59					2
1	Mat	3	High	0	270	Low	2	43.34	33.18					2
1	Mat	4	High	0	270	Low	2	42.95	33.1					2
1	Mat	5	High	0	270	Low	2	42.6	46.07					2
2	Mat	1	High	0	270	Low	2	44.11	56.86					2
2	Mat	2	High	0	270	Low	2	43.34	43.7					2
2	Mat	3	High	0	270	Low	2	39.18	45.03					2
2	Mat	4	High	0	270	Low	2	39.15	49.65					2
2	Mat	5	High	0	270	Low	2	43	43.56					2
3	Long	1	High	0	270	Low	2	50.98	52.65					2
3	Long	2	High	0	270	Low	2	45.52	24.06					2
3	Long	3	High	0	270	Low	2	51	52.9					2
3	Long	4	High	0	270	Low	2	45	24.11					2
3	Long	5	High	0	270	Low	2	72	68.12					2
4	Long	1	High	0	270	Low	2	33.68	42					2
4	Long	2	High	0	270	Low	2	32.14	42.91					2
4	Long	3	High	0	270	Low	2	31.9	40.08					2
4	Long	4	High	0	270	Low	2	33.2	40.82					2

S	Pri	R	Alt	Jit	Az	Pow	K	TK1	TK2	TK3	TK4	TK5	TK6	Eng
4	Long	5	High	0	270	Low	2	33.26	39					2
5	Short	1	High	0	270	Low	2	52.02	47.44					2
5	Short	2	High	0	270	Low	2	52.13	47.42					2
5	Short	3	High	0	270	Low	1	51.34						2
5	Short	4	High	0	270	Low	2	51.23	47.54					2
5	Short	5	High	0	270	Low	2	51.04	47.62					2
6	Short	1	High	0	270	Low	2	31.45	30.12					2
6	Short	2	High	0	270	Low	2	31.58	30.23					2
6	Short	3	High	0	270	Low	2	30.58	30.41					2
6	Short	4	High	0	270	Low	2	31.49	30.46					2
6	Short	5	High	0	270	Low	2	30	30.55					2
7	Short	1	High	0	270	Low	4	35.66	22.44	21	21.71			4
7	Short	2	High	0	270	Low	4	35.66	22.63	22.97	21.71			4
7	Short	3	High	0	270	Low	4	36.17	18.89	21.49	28.6			4
7	Short	4	High	0	270	Low	4	36.03	18.7	12	22.17			4
7	Short	5	High	0	270	Low	4	50.27	19.24	16.71	20.16			4
8	Mat	1	High	0	270	Low	3	29.92	29.41	31.49				3
8	Mat	2	High	0	270	Low	3	35.16	25.63	24.47				3
8	Mat	3	High	0	270	Low	3	29.85	27.56	24.49				3
8	Mat	4	High	0	270	Low	3	34.75	24.34	24.68				3
8	Mat	5	High	0	270	Low	3	30.01	31.75	28.45				3
9	Long	1	High	0	270	Low	1	48.06						1
9	Long	2	High	0	270	Low	1	51.68						1
9	Long	3	High	0	270	Low	1	47.34						1
9	Long	4	High	0	270	Low	1	46.83						1
9	Long	5	High	0	270	Low	1	48.23						1
1	Mat	1	Low	0	270	Low	2	40.37	30.11					2
1	Mat	2	Low	0	270	Low	2	39.24	26.81					2
1	Mat	3	Low	0	270	Low	2	39.53	34.65					2
1	Mat	4	Low	0	270	Low	2	41.37	26.72					2
1	Mat	5	Low	0	270	Low	2	39.22	26.72					2
2	Mat	1	Low	0	270	Low	2	38.53	49.18					2
2	Mat	2	Low	0	270	Low	2	40.66	37.85					2
2	Mat	3	Low	0	270	Low	2	38.43	39.57					2
2	Mat	4	Low	0	270	Low	2	37.85	38.86					2
2	Mat	5	Low	0	270	Low	2	39.21	38.59					2
3	Long	1	Low	0	270	Low	2	47.33	54.22					2
3	Long	2	Low	0	270	Low	2	43.18	56.65					2
3	Long	3	Low	0	270	Low	2	43.55	48.12					2
3	Long	4	Low	0	270	Low	2	42.18	48.61					2
3	Long	5	Low	0	270	Low	2	42	48.46					2
4	Long	1	Low	0	270	Low	3	36.56	30.78	11.79				3
4	Long	2	Low	0	270	Low	3	35.98	29.11	26.38				3
4	Long	3	Low	0	270	Low	3	36	27	24.21				3
4	Long	4	Low	0	270	Low	3	36.58	29.93	24.67				3
4	Long	5	Low	0	270	Low	2	39	40.96					2

S	Pri	R	Alt	Jit	Az	Pow	K	TK1	TK2	TK3	TK4	TK5	TK6	Eng
5	Short	1	Low	0	270	Low	3	46.72	45.3	0.65				3
5	Short	2	Low	0	270	Low	3	49.09	26	44.46				3
5	Short	3	Low	0	270	Low	3	53.61	22.41	44.94				3
5	Short	4	Low	0	270	Low	3	46.12	36.84	1.94				4
5	Short	5	Low	0	270	Low	3	46.57	45.3	0.72				3
6	Short	1	Low	0	270	Low	2	34.57	27.03					2
6	Short	2	Low	0	270	Low	2	34.33	30.71					2
6	Short	3	Low	0	270	Low	2	35.49	26.65					2
6	Short	4	Low	0	270	Low	2	37.42	35.91					2
6	Short	5	Low	0	270	Low	2	33.77	27.12					2
7	Short	1	Low	0	270	Low	4	25.96	14.93	50.38	11.38			4
7	Short	2	Low	0	270	Low	4	26.47	12.26	50.38	11.38			4
7	Short	3	Low	0	270	Low	4	29.49	11.6	50.48	11.32			4
7	Short	4	Low	0	270	Low	4	25.96	12.56	50.2	1.86			4
7	Short	5	Low	0	270	Low	4	36.32	13.06	33.67	1.94			4
8	Mat	1	Low	0	270	Low	3	52.74	19.98	18.37				3
8	Mat	2	Low	0	270	Low	3	52.99	22.88	17.45				3
8	Mat	3	Low	0	270	Low	3	52.74	19.98	17.41				3
8	Mat	4	Low	0	270	Low	3	53.06	19.98	16.83				3
8	Mat	5	Low	0	270	Low	3	59.77	15.75	18.97				3
9	Long	1	Low	0	270	Low	2	44.05	3.36					2
9	Long	2	Low	0	270	Low	1	53.79						1
9	Long	3	Low	0	270	Low	2	49.95	1.94					2
9	Long	4	Low	0	270	Low	2	43.85	3					2
9	Long	5	Low	0	270	Low	1	53.79						1
1	Mat	1	High	0	360	Low	2	43.64	33.1					2
1	Mat	2	High	0	360	Low	2	45.66	32.59					2
1	Mat	3	High	0	360	Low	2	43.34	33.18					2
1	Mat	4	High	0	360	Low	2	42.95	33.1					2
1	Mat	5	High	0	360	Low	2	42.6	46.07					2
2	Mat	1	High	0	360	Low	2	44.11	56.86					2
2	Mat	2	High	0	360	Low	2	43.34	43.7					2
2	Mat	3	High	0	360	Low	2	39.18	45.03					2
2	Mat	4	High	0	360	Low	2	39.15	49.65					2
2	Mat	5	High	0	360	Low	2	43	43.56					2
3	Long	1	High	0	360	Low	3	66.99	30.07	19.85				3
3	Long	2	High	0	360	Low	3	67.06	35.80	18.26				3
3	Long	3	High	0	360	Low	3	67.07	29.82	20.48				3
3	Long	4	High	0	360	Low	1	93.09						2
3	Long	5	High	0	360	Low	3	67.02	29.68	19.69				3
4	Long	1	High	0	360	Low	3	38.59	40.82	20.46				3
4	Long	2	High	0	360	Low	3	37.85	40.31	22.47				3
4	Long	3	High	0	360	Low	3	40.99	36.48	20.60				3
4	Long	4	High	0	360	Low	3	38.08	44.40	19.79				3
4	Long	5	High	0	360	Low	3	38.08	41.47	20.47				3
5	Short	1	High	0	360	Low	3	62.87	21.93	10.93				3

S	Pri	R	Alt	Jit	Az	Pow	K	TK1	TK2	TK3	TK4	TK5	TK6	Eng
5	Short	2	High	0	360	Low	3	63.94	26.61	12.01				3
5	Short	3	High	0	360	Low	3	53.96	23.30	13.84				4
5	Short	4	High	0	360	Low	3	56.12	22.68	14.97				3
5	Short	5	High	0	360	Low	3	64.16	24.00	10.02				3
6	Short	1	High	0	360	Low	2	39.01	29.17					2
6	Short	2	High	0	360	Low	2	36.51	30.56					2
6	Short	3	High	0	360	Low	2	36.00	31.09					2
6	Short	4	High	0	360	Low	2	35.93	30.56					2
6	Short	5	High	0	360	Low	2	37.17	30.46					2
7	Short	1	High	0	360	Low	4	49.82	44.72	39.00	28.13			4
7	Short	2	High	0	360	Low	4	23.53	37.93	44.32	29.81			4
7	Short	3	High	0	360	Low	4	50.10	36.96	44.54	29.80			4
7	Short	4	High	0	360	Low	4	53.35	36.00	43.57	29.36			4
7	Short	5	High	0	360	Low	4	57.04	37.15	41.19	28.04			4
8	Mat	1	High	0	360	Low	3	39.65	33.00	24.45				3
8	Mat	2	High	0	360	Low	3	40.46	31.91	24.64				3
8	Mat	3	High	0	360	Low	2	47.54	27.00					2
8	Mat	4	High	0	360	Low	3	46.78	29.96	25.56				3
8	Mat	5	High	0	360	Low	3	40.65	32.51	24.64				3
9	Long	1	High	0	360	Low	2	48.06	20.47					2
9	Long	2	High	0	360	Low	1	57.84						1
9	Long	3	High	0	360	Low	2	48.23	24.93					2
9	Long	4	High	0	360	Low	2	48.23	14.44					2
9	Long	5	High	0	360	Low	1	63.91						1
1	Mat	1	Low	0	360	Low	3	40.37	30.11	11.53				3
1	Mat	2	Low	0	360	Low	3	39.78	33.57	14.89				3
1	Mat	3	Low	0	360	Low	3	40.62	27.88	11.05				3
1	Mat	4	Low	0	360	Low	3	46.11	24.12	12.6				3
1	Mat	5	Low	0	360	Low	3	45.81	24.65	12.61				3
2	Mat	1	Low	0	360	Low	2	38.53	49.18					2
2	Mat	2	Low	0	360	Low	2	40.66	37.85					2
2	Mat	3	Low	0	360	Low	2	38.43	39.57					2
2	Mat	4	Low	0	360	Low	2	37.85	38.86					2
2	Mat	5	Low	0	360	Low	2	39.21	38.59					2
3	Long	1	Low	0	360	Low	2	73.35	41.72					2
3	Long	2	Low	0	360	Low	3	61.81	31.94	40.64				3
3	Long	3	Low	0	360	Low	3	61.88	32.69	65.34				3
3	Long	4	Low	0	360	Low	3	61.76	31.95	40.64				3
3	Long	5	Low	0	360	Low	3	61.81	33	40.48				3
4	Long	1	Low	0	360	Low	3	36.56	30.78	21.93				3
4	Long	2	Low	0	360	Low	3	36	30.89	21				3
4	Long	3	Low	0	360	Low	3	38.65	40.83	14.68				3
4	Long	4	Low	0	360	Low	3	36	25.36	25.1				3
4	Long	5	Low	0	360	Low	3	36.38	27	25.04				3
5	Short	1	Low	0	360	Low	4	53.95	24	13.4	29.04			4
5	Short	2	Low	0	360	Low	4	56.16	18.44	14.15	29.21			4

S	Pri	R	Alt	Jit	Az	Pow	K	TK1	TK2	TK3	TK4	TK5	TK6	Eng
5	Short	3	Low	0	360	Low	4	52.72	19.51	15	32.84			4
5	Short	4	Low	0	360	Low	4	61.67	18.92	11.79	29.9			4
5	Short	5	Low	0	360	Low	4	56.99	18.45	14.14	29.03			4
6	Short	1	Low	0	360	Low	3	14.57	27.03	38.27				3
6	Short	2	Low	0	360	Low	3	37.27	25.41	55.68				3
6	Short	3	Low	0	360	Low	3	36	27	38.03				3
6	Short	4	Low	0	360	Low	3	37.91	25.16	37.79				3
6	Short	5	Low	0	360	Low	3	33.7	32.99	37.81				3
7	Short	1	Low	0	360	Low	4	45.79	42.43	42	32.05			4
7	Short	2	Low	0	360	Low	4	47.13	36	45.22	33			4
7	Short	3	Low	0	360	Low	4	46.95	39.83	42.17	29.51			4
7	Short	4	Low	0	360	Low	4	46.95	41.56	41.01	26.46			4
7	Short	5	Low	0	360	Low	4	46.11	35.8	45.59	33.72			4
8	Mat	1	Low	0	360	Low	3	36.32	33.1	18.54				3
8	Mat	2	Low	0	360	Low	3	42.83	29.9	19.05				3
8	Mat	3	Low	0	360	Low	3	37.43	35.11	13.73				3
8	Mat	4	Low	0	360	Low	3	37.92	35.11	17.56				3
8	Mat	5	Low	0	360	Low	3	36.42	36.29	16.83				3
9	Long	1	Low	0	360	Low	2	44.05	3.36					2
9	Long	2	Low	0	360	Low	2	53.79	2.94					2
9	Long	3	Low	0	360	Low	2	43.7	3					2
9	Long	4	Low	0	360	Low	2	44.48	3					2
9	Long	5	Low	0	360	Low	2	44.86	4.03					2
1	Mat	1	Low	0	360	High	3	26.81	19.98	27.57				3
1	Mat	2	Low	0	360	High	4	28.5	20	19.9	0.605			4
1	Mat	3	Low	0	360	High	3	26.54	23.91	21.19				3
1	Mat	4	Low	0	360	High	4	26.94	19.98	19.07	0.605			4
1	Mat	5	Low	0	360	High	3	30	24.33	4.815				3
2	Mat	1	Low	0	360	High	3	29.93	25.08	26.03				3
2	Mat	2	Low	0	360	High	3	29.93	29.14	24.73				3
2	Mat	3	Low	0	360	High	3	35	23.22	24.68				3
2	Mat	4	Low	0	360	High	3	29.93	25.11	25.95				3
2	Mat	5	Low	0	360	High	3	29.56	28.65	24.67				3
3	Long	1	Low	0	360	High	5	32.07	31.55	27.41	16.95	32.03		5
3	Long	2	Low	0	360	High	5	32.33	31.85	27.41	16.96	26.64		5
3	Long	3	Low	0	360	High	5	32.07	31.55	27.33	16.61	26.75		5
3	Long	4	Low	0	360	High	5	32.06	31.61	27.49	16.89	29.25		5
3	Long	5	Low	0	360	High	5	31.84	37.5	29.7	30.38	2.26		5
4	Long	1	Low	0	360	High	4	25.43	25.96	22.5	25.97			4
4	Long	2	Low	0	360	High	4	25.64	25.99	22.71	25.82			4
4	Long	3	Low	0	360	High	4	25.46	25.89	22.57	25.76			4
4	Long	4	Low	0	360	High	4	28.97	24.49	29.36	3.09			4
4	Long	5	Low	0	360	High	4	25.64	26.04	22.57	33.73			4
5	Short	1	Low	0	360	High	5	31.51	21.84	25.54	24.16	14.16		5
5	Short	2	Low	0	360	High	5	35.89	20.78	24.78	22.19	14.55		5
5	Short	3	Low	0	360	High	5	31.64	21.73	25.54	23.37	14.9		5

S	Pri	R	Alt	Jit	Az	Pow	K	TK1	TK2	TK3	TK4	TK5	TK6	Eng
5	Short	4	Low	0	360	High	5	31.5	23.88	27.99	18.11	16.18		5
5	Short	5	Low	0	360	High	6	31.5	22.08	26.37	11.22	14	12.79	6
6	Short	1	Low	0	360	High	4	32.91	32.7	13.1	18.46			4
6	Short	2	Low	0	360	High	4	28.47	32.74	13.1	18.41			4
6	Short	3	Low	0	360	High	3	32.73	42.19	21.21				3
6	Short	4	Low	0	360	High	4	28.61	39	12.64	16.13			4
6	Short	5	Low	0	360	High	6	31.5	22.08	26.37	11.22	14	12.79	6
7	Short	1	Low	0	360	High	5	28.09	30.62	34.16	28.35	12.97		5
7	Short	2	Low	0	360	High	5	28.33	30.56	32.17	26.02	11.76		5
7	Short	3	Low	0	360	High	5	31.97	28.99	30.07	26.16	12.38		5
7	Short	4	Low	0	360	High	5	30.14	29.38	34.15	25.81	11.16		5
7	Short	5	Low	0	360	High	5	28.5	30.7	34.23	25.88	11.16		5
8	Mat	1	Low	0	360	High	4	27.14	31.09	21.06	29.83			4
8	Mat	2	Low	0	360	High	4	27	31.09	24.19	24.28			4
8	Mat	3	Low	0	360	High	4	27.17	31.34	21.18	24.44			4
8	Mat	4	Low	0	360	High	4	28.72	30.97	23.98	24.28			4
8	Mat	5	Low	0	360	High	4	28.64	36.98	15.51	29.88			4
9	Long	1	Low	0	360	High	3	35.34	17.82	32.41				3
9	Long	2	Low	0	360	High	3	29.92	21	28.41				3
9	Long	3	Low	0	360	High	3	29.92	21.02	28.42				3
9	Long	4	Low	0	360	High	3	31.72	22.63	11.59				3
9	Long	5	Low	0	360	High	3	29.5	21.17	28.3				3
1	Mat	1	Low	5x	360	High	0							0
1	Mat	2	Low	5x	360	High	0							0
1	Mat	3	Low	5x	360	High	0							0
1	Mat	4	Low	5x	360	High	0							0
1	Mat	5	Low	5x	360	High	0							0
2	Mat	1	Low	5x	360	High	0							0
2	Mat	2	Low	5x	360	High	0							0
2	Mat	3	Low	5x	360	High	0							0
2	Mat	4	Low	5x	360	High	0							0
2	Mat	5	Low	5x	360	High	0							0
3	Long	1	Low	5x	360	High	0							0
3	Long	2	Low	5x	360	High	0							0
3	Long	3	Low	5x	360	High	0							0
3	Long	4	Low	5x	360	High	0							0
3	Long	5	Low	5x	360	High	0							0
4	Long	1	Low	5x	360	High	0							0
4	Long	2	Low	5x	360	High	0							0
4	Long	3	Low	5x	360	High	0							0
4	Long	4	Low	5x	360	High	0							0
4	Long	5	Low	5x	360	High	0							0
5	Short	1	Low	5x	360	High	0							1
5	Short	2	Low	5x	360	High	0							1
5	Short	3	Low	5x	360	High	0							1
5	Short	4	Low	5x	360	High	1	26.5						1

S	Pri	R	Alt	Jit	Az	Pow	K	TK1	TK2	TK3	TK4	TK5	TK6	Eng
5	Short	5	Low	5x	360	High	1	56.38						1
6	Short	1	Low	5x	360	High	0							0
6	Short	2	Low	5x	360	High	0							0
6	Short	3	Low	5x	360	High	0							0
6	Short	4	Low	5x	360	High	0							0
6	Short	5	Low	5x	360	High	0							0
7	Short	1	Low	5x	360	High	1	16.71						1
7	Short	2	Low	5x	360	High	1	17.65						1
7	Short	3	Low	5x	360	High	1	20.92						1
7	Short	4	Low	5x	360	High	1	16.36						1
7	Short	5	Low	5x	360	High	1	20.51						1
8	Mat	1	Low	5x	360	High	0							0
8	Mat	2	Low	5x	360	High	0							0
8	Mat	3	Low	5x	360	High	0							0
8	Mat	4	Low	5x	360	High	0							0
8	Mat	5	Low	5x	360	High	0							0
9	Long	1	Low	5x	360	High	1	12.09						1
9	Long	2	Low	5x	360	High	1	12.28						1
9	Long	3	Low	5x	360	High	1	15.56						1
9	Long	4	Low	5x	360	High	1	12.08						1
9	Long	5	Low	5x	360	High	1	12.28						1

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14. ABSTRACT

In March 2000, the High Energy Laser Executive Review Panel presented the Department of Defense Laser Master Plan, which reported that HEL weapons are ready for offensive and defensive applications. One candidate platform capable of performing some of the reported applications is the Advanced Tactical Laser (ATL), an Advanced Concept Technology Demonstration program which places a high energy laser weapon on a tactical aircraft, such as the V-22, C-130, or H-47. A way of assessing the utility of a new weapon system and the benefits of its inclusion in the force structure is the use of combat models. This research examines, by example, issues involved with modeling an airborne tactical high energy laser weapon in a mission level combat simulation, and evaluates possibilities to aggregate simulation results into higher level, campaign models.

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